Rock mass seismic response to mining: a tool for validating critical assumptions

W. de Beer[a], R. William[b], S. Prahastudhi[b] and M. Braim[c]
[a]*ESG Solutions Australia*
[b]*ESG Solutions Indonesia*
[c]*ESG Solutions Canada*

ABSTRACT

In underground mining, the main use of passive seismic data remains hazard assessment in various forms. However, with an appropriate sensor array it is possible to move towards conclusions about the state and fabric of the rock mass at a given time. The state of the rock mass is described by stress, deformation, and physical condition. The fabric is described by joints, bedding planes, pre-existing failure plains, lithology, and geological structures.

Generally, geophysical methods do not provide absolute numbers. However, locations of density or velocity contrasts, seismic source mechanisms and stress directions can be determined. Relative quantities, requiring time lapse methods and/or careful spatial comparisons are common. This paper focusses on combining stress inversions using seismic moment tensors and passive seismic tomography. Stress inversions are useful in describing the state of the rock mass at a given time and place. Tomographic methods are useful for tracking the influence of mining on the surrounding rock. Tomographic methods also provide information in areas where there is no seismic activity, but which are traversed by seismic radiation. Advances in computation capability and innovative algorithms make these techniques accessible to geotechnical practitioners.

Here, we apply these techniques to a block cave. The aim is to facilitate geological and geotechnical model validation which aids in the enhancement of understanding hazard in mining operations by understanding the evolution of stress distribution in the rock.

1 INTRODUCTION

Seismic monitoring systems acquire real-time data in mines all around the world. These systems deliver rich multidimensional data sets which are predominantly used for short-term hazard assessment and risk management. However, a mine is a multi-decade undertaking from exploration, thorough resource estimation, feasibility studies, design, construction, operation to closure and remediation. In the exploration, resource estimation and feasibility study phases, a substantial body of information is collected and collated into geological models. During the design phase rock mass characterisation is key. (Brown, 2007) defines rock mass characterisation as the systematic process of quantitatively and qualitatively describing a rock mass for engineering purposes. The design and feasibility study (Brown, 2007) involve the selection of mining method, detailed design of underground excavations (size, shape, support requirements), infrastructure location and design, impacts of mining (environmental and local communities), and risk assessments (rock bursts, major instabilities), rock fragmentation studies, production level design, surface subsidence. The data used include geology, surface and groundwater geology, topography, environmental, and geotechnical. There is significant lag between studies and mining, when the rock mass is accessed directly, and the validity of any assumptions tested. The collection, analysis and interpretation of exploration data are complex and there are always ambiguities and contradictions. Once established, geotechnical models are rarely modified, even if new information comes to hand.

Underground or surface mining perturbs the existing stress equilibrium (Gibowicz and Kijko, 1994). Some stress is transferred into the surrounding rock mass. In underground mining the transferred stress can increase the ambient stress beyond the intact rock strength near excavations where the nearby free surface allows movement It can exceed frictional clamping on faults, which leads to fault slip, or it can cause slipping or buckling in or near stiffness contrasts, for example between strong brittle intrusive complexes and other, softer lithologies. The result is the transfer of stress to other locations which can experience sudden inelastic deformation (seismic events), or lead to stress changes below the detectability limit of a monitoring system. The former can be used to learn more about the rock mass properties at the location of the events, while the latter response could be detected by tomographic methods.

In this paper, we show how seismicity from two block caves, one above the other, was studied in near real time for up-to-date information on local stress regimes and some rock properties (e.g., damage, failure plane orientations). The mine was in a mountainous area, exploiting skarns hosted in sedimentary rocks and a limestone group. The sedimentary rocks are deformed by kilometer-scale folds containing subvertical reverse and thrust faults. Superimposed on this is a left-lateral strike-slip reactivation of reverse faults. The source of the mineralization are intrusive complexes formed by I-type calc-alkalic magmas. The hanging wall mineralization boundary is a skarn reaction front in sudden contact with barren marble. The geological environment of the mine is therefore characterized by strong stiffness contrasts between diorites, skarns, and marble, and by several mine- and regional-scale faults intersecting the caves. The upper block cave was mature and almost fully exploited, resulting in a large mass of moving subsidence rock.

The creation of a large rubble-filled cave in block caving results in a commensurately large zone of influence hundreds or thousands of meters away from the cave. The examination of the stress, deformation, and resultant change to rock structure beyond the immediate mining horizon presents opportunities to tactically adjust mining planning and geotechnical models before development reaches the relevant locations.

1.1 Source mechanisms

Seismic events emit a radiation pattern that depends on the orientation of the source. There are three fundamental fracture types: shear, tensile opening, and tensile closure. Composite and more complex failures are constructed from combinations of these. In the bulk rock mass, the seismic source mechanism is approximated by a set of equivalent forces which produce particle displacements or strains in the rock identical to those from the actual forces of the physical process at the source (Jost and Herrman, 1989). Each pair of forces produces a moment and the ground displacement at a sensor is given by a convolution of a Greens Function, which represents the response of the rock mass to forces (elastic stress/strain response), and the Seismic Moment Tensor (SMT). Close to excavations, the model may require modification as the excavations may form part of the source.

The particle displacements are combinations of strains inward towards, and outward away, from the source. The SMT be solved for by matrix inversion to yield pressure-compressional (P) and tensile (T) strain axis directions and a decomposition of the SMT. The SMT can be decomposed into a combination of volume change, fracture opening and closing, also called the isometric component; shear, the double couple component; and the compensated linear vector dipole (CLVD) component, a hybrid mechanism. The solutions also determine two possible failure planes. The result of the SMT inversion can be summarized in a “beach ball” diagram which represents the inner lower focal hemisphere projection of the first motions at the source and the traces of the complimentary failure planes (Figure 1).

In mining, pure slip events are rare. They are associated with planar structures such as faults and dykes and occasionally movement along lithological contacts well away from excavations. The Hudson source type plot (Hudson, 1989) in Figure 1 displays the three components of the SMT solution in a uniform manner. Figure 1 also relates the Hudson source type plot to common mine seismic event mechanisms. Using multiple SMTs, a stress inversion can be performed to understand the stress field.

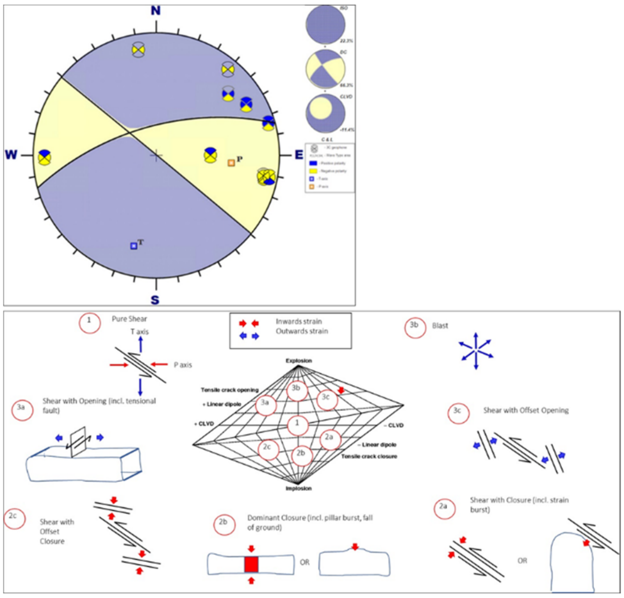

Figure 1 Top: decomposition of the inverted Seismic Moment Tensor of an event into tensile crack opening (+22% isometric), shear (66.3%) and compensated vector dipole (-11.4%), projected on the lower hemisphere of the focal sphere. Bottom: relationship between common mine seismic events and SMT decomposition summarized on Hudson source type diagrams. After (Hudson et al, 1989).

1.2 Stress inversion

Seismic stress inversion estimates the most likely local principal stress directions given the observed failure planes from seismic moment tensors. It also provides the shape ratio, an estimate of the relative principal stress magnitudes.

We implement the stress inversion using (Vavryčuk, 2014), based on one of the standard methods for determining a single-stress tensor that best fits a set of focal mechanisms (Michael, 1984). The technique minimizes the difference between the slip vector and the resolved shear stress vector on each fault plane. A Mohr-Coulomb failure criterion (Figure 2) is used to estimate the orientation of the principal stress direction which maximizes the instability of the potential failure planes.

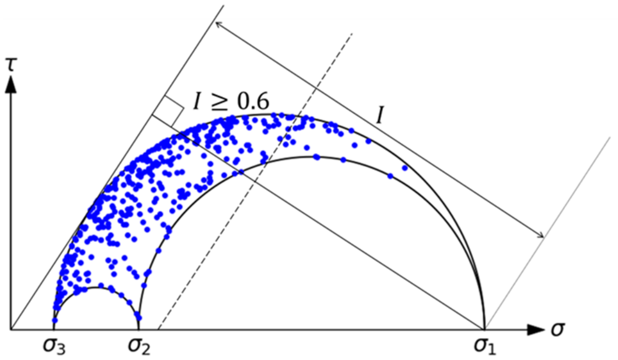

Figure 2 Mohr circle representing a single-stress tensor that best fits a set of focal mechanisms, with the individual inverted stress tensors for each event (blue dots). $I \geq 0.6$ indicates event / failure plane combinations most likely associated with failure.

1.3 Stress inversion

Rock fracturing generates seismic waves, which propagate with different velocities through parts of the rock mass with different moduli. Seismic tomography allows the reconstruction of changes in seismic velocities related to rock property variations by inverting the travel times of seismic waves. The variation of P wave (V_P) and S wave (V_S) velocity can help interpret lithology, stress, and the state of deformation or damage.

V_P is a combination of bulk and shear modulus normalized by material density and V_S is shear modulus normalized by material density. Areas of increasing stress should show increasing velocities. Increasing stress translates to closing joints, fractures and microcracks along grain boundaries of rock, and to increasing stiffness of the rock. Areas of decreasing velocities can be interpreted as de-stressing and/or post-peak rock failure. The sensitivity of body wave velocity to stress varies from approximately 0.1% to 1% change in velocity when stress changes (Niu et al., 2008; Silver et al, 2007; Yamamura, 2003). A stress variation of $10\,MPa$ would yield deviation from the background velocity ranging from 1% to 10%.

The volume of interest is discretised into a grid of 3D volume elements and the events grouped by the volume in which they occur. Using the measured travel times of seismic signals from source-sensor pairs are and a starting velocity model, a 1D background velocity (half space) is perturbed to generate a 3D velocity model. Initial inputs can consist of blasts and microseismic events (anything that can be located accurately). By examining the changes in velocity, cave shapes and stress changes can be estimated. The inversions used here utilized a modified form of the Simultaneous Iterative Reconstruction Technique (SIRT) (Tarantola and Valette, 1982, Crowley et al, 2015).

1.4 Collapsing

The point locations calculated from a seismic system may obscure possible regular patterns in spatial distribution of events. The collapsing method (Jones and Stewart, 1997) enhances the spatial distribution of calculated seismic event locations by moving the location solutions inside their uncertainty ellipsoids until a distribution is obtained that is internally consistent. It assumes that event location uncertainties are normally distributed and that event locations within the corresponding ellipsoids of uncertainty are random. It tends to exaggerate linear features in the event locations.

If event locations collapse to linear patterns, a linear geological structure could be inferred. This is a simple way to examine if a rock mass has any obvious dominant structures. If no clear structures are delineated, more subtle sources may be involved.

2 METHODS

2.1 Data set: large block between two mine scale faults

Figure 3 shows a large block of rock behind the slope of the upper cave (Cave 01) subsidence zone, bounded by northeast – southwest trending vertical mine scale faults. Cave 01 is above and laterally offset from Cave 02. Seismicity was characterized by frequent large, slow and complex events in a soft rock environment with no damage to mine infrastructure. The moment tensor solutions for the large events suggested an association with the geological structures and was speculated to be related to large blocks of rock moving vertically along the faults.

Historical exploration drilling data did not indicate additional large geological structures between the regional scale structures. The locations of 8132 events were collapsed, with inconclusive results (Figure 4). A stress inversion was performed using 223 moment tensor solutions which exhibited varying mechanisms and failure types (Figure 4) but which did show discernable trends in the P and T axes. The stress inversion indicated that there was a stress and failure plane combination that described instability (Figure 6), i.e., a propensity for the rock mass to fail in preferred directions.

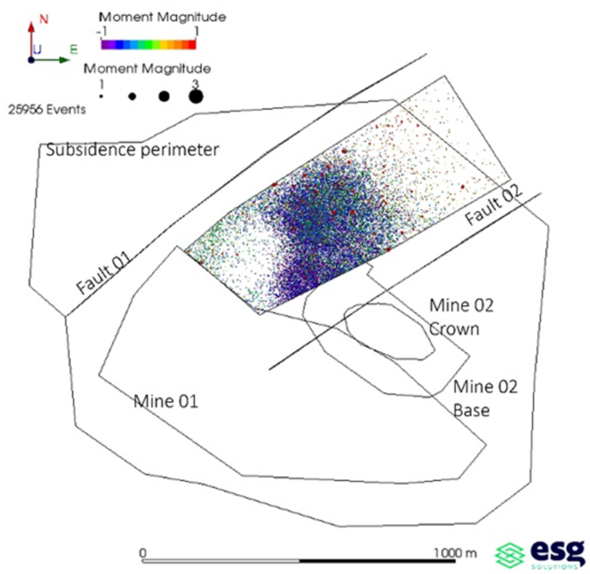

Figure 3 Seismicity in block between two mine scale faults over an 11-month period. Events are colored by moment magnitude.

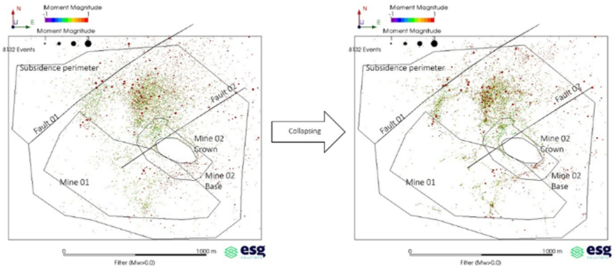

Figure 4 **Collapsing event clouds in this case not yielding any obvious linear features.**

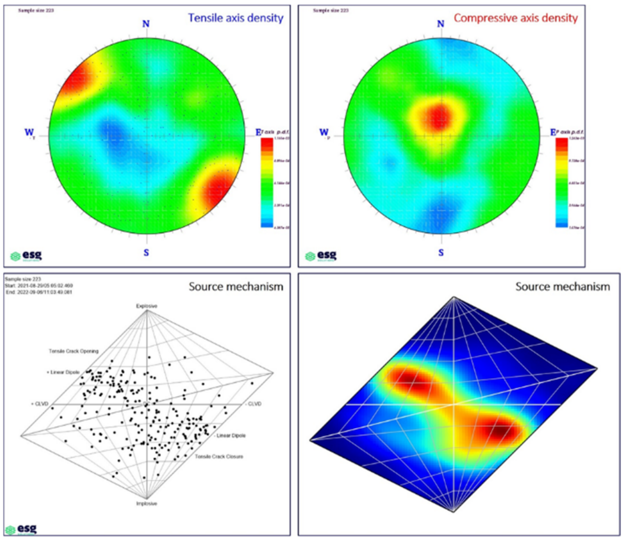

Figure 5 **Clockwise from top left: tensile (T) strain axis density, compressive (P) axis density, Hudson source type diagram.**

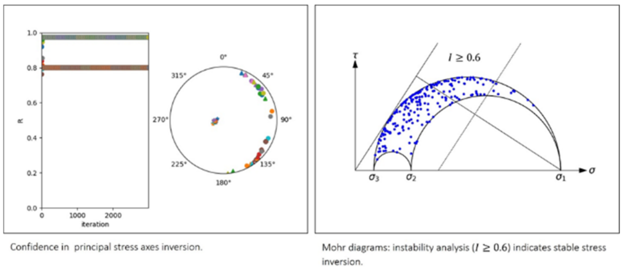

Figure 6 **Convergence of the stress inversion (left) and instability of the most likely solutions (Mohr circle on the right).**

2.2 Data set: cave abutment

The alteration of the local stress field around an excavation increases with the size of the excavation (Brady and Brown, 2004). Seismic events occurring in the abutments of an excavation are the result of this perturbation. Abutment seismicity therefore presents an opportunity to learn more of both the effect of the excavation and the rock mass itself.

2.3 Stress inversions

A region to the northwest of the developing Cave 02 became seismically active and remained so for several years (Figure 7). The seismicity was located in a region between the same faults discussed previously, but approximately 400 m deeper. To form an impression of the change in stress as the cave front approached, two overlapping time periods were considered. Overlapping was needed to have enough moment tensor solutions for stable stress inversions. The collapse analysis of the solutions in the two overlapping time periods showed no linear patterns. In Time Span 01, 158 events had suitable moment tensor solutions. Time Span 02 had 183 events with suitable moment tensor solutions. The mechanisms and failure types varied (Figure 8) but trends in the P and T axes were evident. A stress inversion, presented in Figure 9, indicated that there was a stress and failure plane combination that described instability, i.e., a propensity for the rock mass to fail in preferred directions.

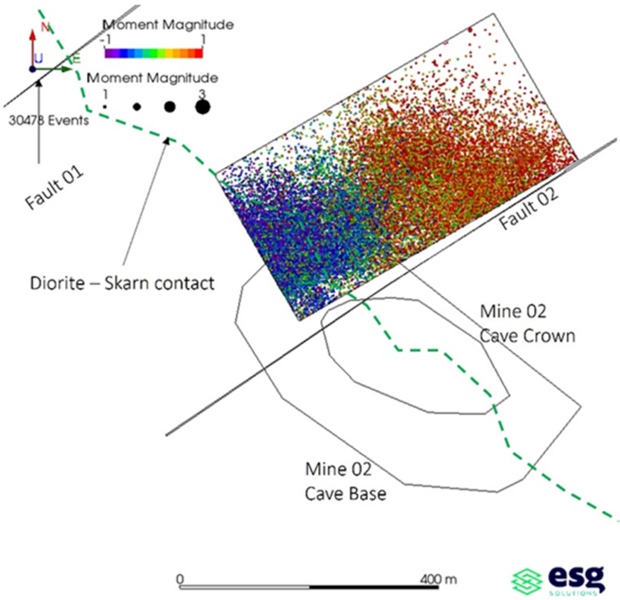

Figure 7 **Seismicity in cave abutment of a cave. Events are colored by moment magnitude.**

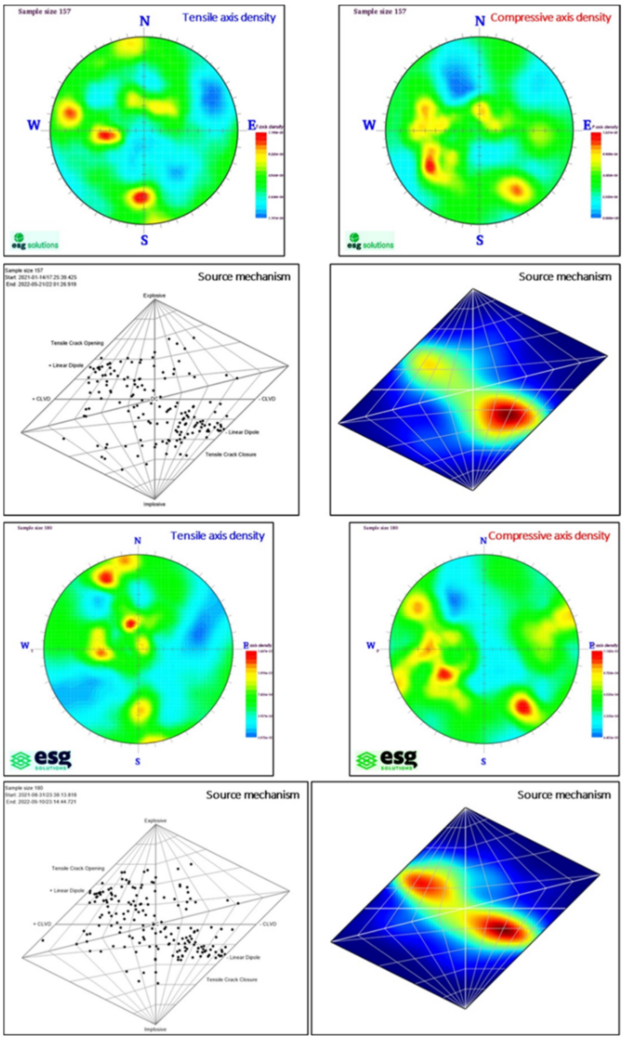

Figure 8 Top: Clockwise from top left: tensile (T) strain axis density, compressive (P) axis density, Hudson source type diagram, Time Span 01, in cave abutment. Bottom: same for Time Span 02.

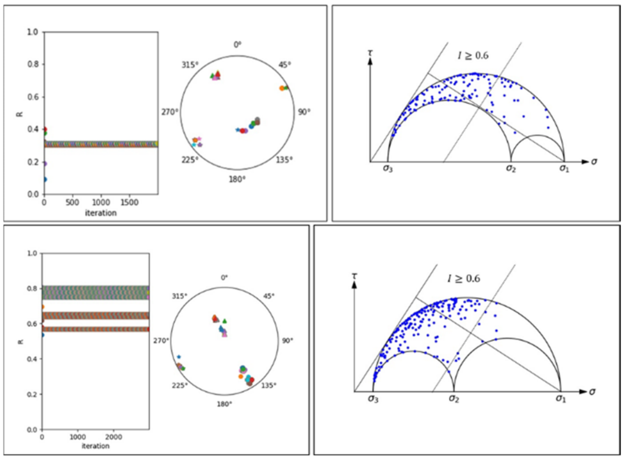

Figure 9 Top: Convergence of the stress inversion (left) and instability of the most likely solutions (Mohr circle on the right), Time Span 01, in cave abutment. Bottom: Convergence of the stress inversion (left) and instability of the most likely solutions (Moh circle on the right), Time Span 02, in cave abutment.

2.3.1 Passive seismic tomography

Time lapse passive seismic tomography was performed for Mine 02 in one-month windows to examine the evolution of the abutment. (Figure 10) compares the results to known large-scale lithology. In both time frames, the tomography captures the difference between diorite and skarn at the base of the cave very well. This is to be expected from large, mostly unchanging, geological features.

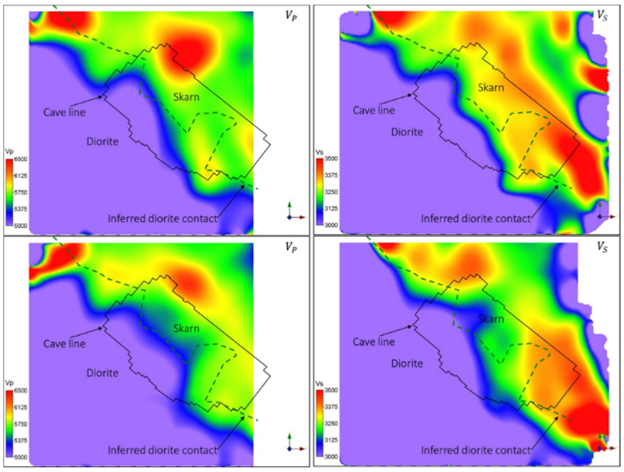

Figure 10 Contours of inverted P-wave velocity (left) and S-wave velocity (right) on a cut plane through the extraction level of Mine 02, Month 01 (top) and Month 02 (bottom). The contrast between low and high inferred velocities roughly follows the contact between stiff and brittle diorite and the skarn.

3 DISCUSSION

3.1 Stress inversions

In the first case study, there was substantial seismic activity in a block between mine-scale faults, but the geological database did not have any structures which could be considered sources for the activity. Collapsing event locations (Figure 4) did not conclusively highlight linear structures, while source mechanisms (Figure 5) were variable, with some indication of dominant opening and closing type mechanisms. Stress inversion results (Table 1 and Figure 11) suggested a steeply dipping to sub-vertical σ_1. The σ_1 direction was consistent with stress measurements (GA, 2018) for depth less than 900 m. The effective failure plane dips steeply (Table 1 and Figure 11). The results are summarized graphically in Figure 11. The failure plane is shown as a single plane, but the interpretation is that, on average, the sense of dislocation is steeply dipping. In other words, many shallow dipping fractures were opening and closing. The hypothesis is that subsidence and downward block movement between the faults were driving bedding plane and / or joint sliding, opening, closing. In other words, there was a lot of collective movement presenting as slow, large-deformation seismic events, rather than slip on faults.

The stress inversion results for the abutment of Cave 02 cave below the large block discussed above (Table 1 and Figure 12) suggests a shallow dipping to sub-horizontal σ_1. The σ_1 direction is consistent with stress measurements (GA, 2018) for depth >900 m roughly consistent with the accepted ambient tectonic stress. The average, effective, failure plane was steeply dipping (Figure 13), and the source mechanisms diverse with some preponderance of opening and closing.

The subsidence and associated rebound (Cave 01) could have been unclamping pre-existing shear zones. At this depth, the stress conditions were still close to the background tectonic situation, but there was some suggestion of local stress rotation by the approaching cave.

Table 1 Principal stress and failure plane solutions

Item	Trend	Plunge
Large block between mine Scale Faults		
σ_1	260^{o}	76^{o}
σ_2	45^{o}	10^{o}
σ_3	136^{o}	7^{o}
Failure plane	25^{o}	64^{o}
Cave abutment – Time Span 01		
σ_1	237^{o}	11^{o}
σ_2	61^{o}	62^{o}
σ_3	332^{o}	24^{o}
Failure plane	14^{o}	60^{o}
Cave abutment – Time Span 02		
σ_1	240^{o}	5^{o}
σ_2	140^{o}	40^{o}
σ_3	337^{o}	49^{o}
Failure plane	17^{o}	71^{o}

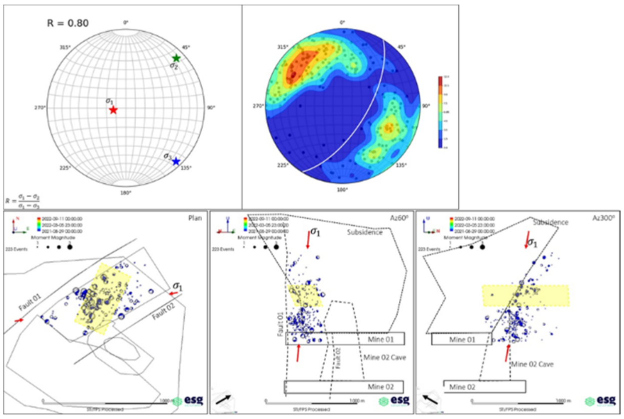

Figure 11 Top: Stable solutions for the principal stress directions, shape factor, and average, effective failure plane in a large block between two mine-scale faults. Bottom: Interpreted σ_1 and failure plane in a large block between two mine-scale faults.

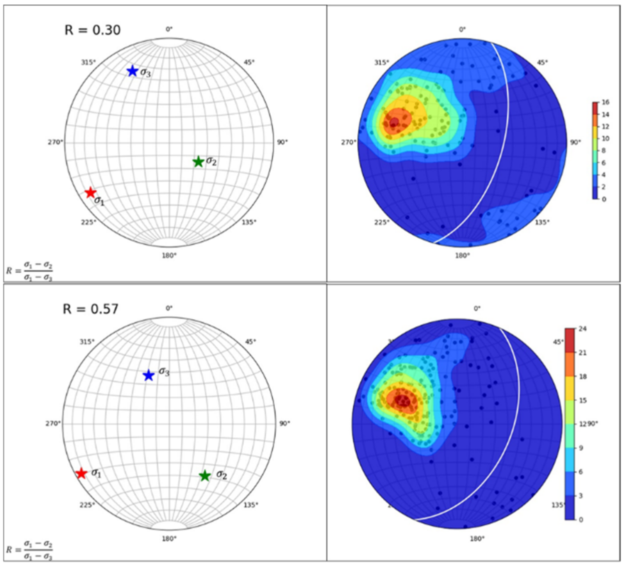

Figure 12 Stable solutions for the principal stress directions and shape factor in the abutment of a cave, Time Span 01 (top) and Time Span 02 (bottom).

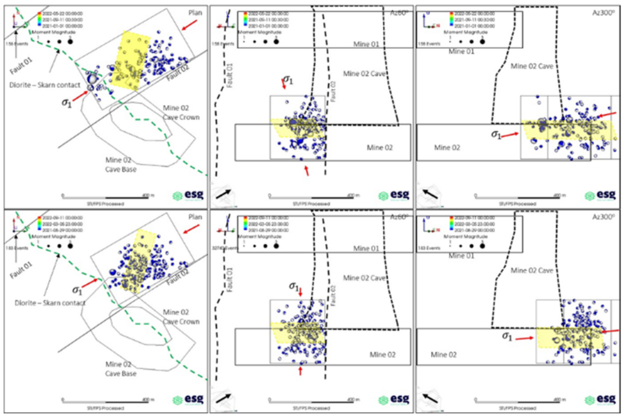

Figure 13 Interpreted σ_1 and failure plane in the abutment of a cave, Time Span 01 (top) and Time Span 02 (bottom).

3.2 Passive seismic tomography

In contrast to the lithological contact in Mine 02 (Figure 10), substantial differences between the two months in the tomographic inversions were evident in the abutment (Figure 14). These time periods were both in Time Span 02 of the stress inversion exercise.

It is important to remember that the presumed cave outline is an abstraction derived from open-hole measurements, height-of draw calculations, and seismic location distributions. There is a lag between measurements and updates, so the presumed outline is always out of date. The cave outline drawing has a sharp boundary between the cave and the host rock, but the transition is more gradual. The inversion grid size is 50 m, which limits the resolution of the method. These factors could partly explain why the tomography results in Figure 14 do not reproduce exactly the abstracted cave outline. Nevertheless, the inversion does capture the general location of the cave.

Comparing the P-wave velocity results in Month 01 and Month 02, and using the P-wave velocity as a proxy for stress, it appears that a larger fraction of the abutments experienced higher stress than the background in Month 01. In Month 02 the higher stress volume was more concentrated and appeared to extend upwards more. The S-wave velocity, which is sensitive to fracture density and orientation, supports this interpretation. It appears as if the further abutment has yielded in the two months, and the higher stresses closer to the assumed cave front are driven by production blasting. In general, the velocity values are lower, indicating lower stress and / or yielded areas.

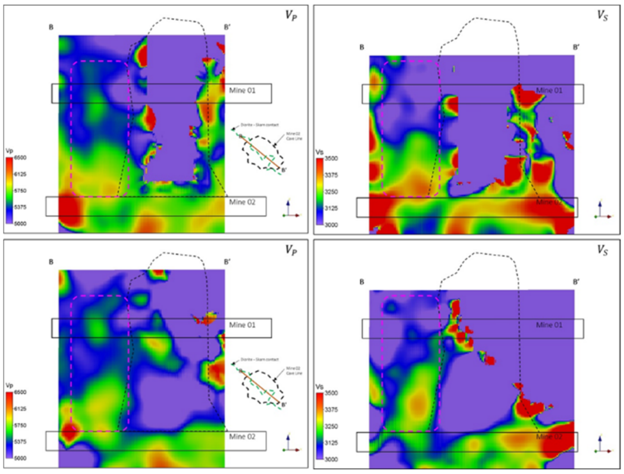

Figure 14 Contours of inverted P-wave velocity (left) and S-wave velocity (right) in the northwestern abutment of the Mine 02 cave, Month 01 (top), and Month 02 (bottom). Cut plane through the centerline of the presumed cave (dotted line). The area of interest is interest is indicated by the dashed magenta oblong.

3.3 Summary

The main current use of mine seismic monitoring systems is short term hazard assessment and risk management. However, if a system can deliver data which can be used for stress inversions and passive tomography, the possibility exists of using the system as a tactical tool. Computing power and algorithms exist to perform clustering, moment tensor inversion, stress inversion and tomographic inversions in near real time.

The data used must conform to strict conditions. Tomographic inversions require uniform spatial distributions of data. Stress inversions require moment tensors which require accurate source locations and at least seven fully operational tri axial sensors in the far field of the source, arranged in a wide (if not fully three dimensional) angular coverage of the focal sphere. P- and S-wave first motions at sensors (including polarization) must be determined accurately as must spectral amplitude measurement from P- and S-waves (P, SV and SH). This means that seismic monitoring arrays must be carefully designed with a mix of sensors and that installation must be done with care and attention to detail. Ongoing preventive maintenance and uncompromising quality control is essential.

Various ways of clustering data, including the collapsing technique shown here, combined with stress inversions to estimate the most likely failure planes (or collections of planes) could provide indications of the rock mass structure ahead of mining. Small faults and dykes are frequently missed during exploration drilling, and topography and other environmental conditions can preclude on-the-ground geophysical techniques. When mine scale faults and dykes are detected, their extent and persistence is mostly a matter of judgement. The expanding stress perturbation and deformation around an excavation activates structures or bedding planes and shear zones. If these activated structures are significant dykes or faults, they have to be approached in a particular fashion.

Local in situ stress is a significant variable which is very hard to determine directly. The world stress map (Heidbach, 2016) does not have the required resolution and is based on tectonic earthquakes at depths far exceeding the deepest mine. The upper 1000 to 3000 m of the crust is heterogenous and disordered and topography can affect local stress conditions. This is important, as the local stress magnitude and direction affects the response of excavations. A large enough excavation can change local principal stress directions. It is therefore important and useful to have a technique that can be applied in near real time to track local stress evolution.

While stress inversion cannot provide absolute values for the stress, the shape factor carries some indication of relative magnitudes of the components. Passive seismic tomography can highlight areas of higher stress than others and can show how the stress changes. An important use of this information is to judge when the stress perturbation ahead of cave development has migrated. This can assist in sequencing mining from low to high stress as well as deciding where to deploy resources in increasing production rate in destressed areas while higher stress areas pass through a stress peak.

Practical use of the results requires some thought and discussion. In most mining scenarios, changing mine layouts rapidly is unfeasible. These changes always mean loss of production and may require retooling, training, and additional people. However, there is considerable room for variation in sequencing and rate of mining which could result in small but important improvements in geometry or stress migration.

ACKNOWLEDGEMENT

The authors wish to thank Samantha Palmer (ESG Solutions Canada) for detailed internal review and suggestions.

REFERENCES

Brady, B. H. G. & Brown, E. T. (2004). Rock Mechanics for Underground Mining, Springer (pp. 197-223).

Brown, E. T. (2007). Block Caving Geomechanics 2nd Ed. – the International Caving Study 1997–2004. University of Queensland, JKMRC Monograph Series in Mining and Mineral Processing 3.

Cox, A. & Hart, R. B. (2009). Plate tectonics: How it works. John Wiley & Sons.

Crowley, J. W., Baig, A. M., Urbancic, T. & Von Lunen, E. (2015). 4D tomography and deformation from microseismic data. Proceedings of the 77th EAGE Conference and Exhibition.

Gibowicz, S. J. & Kijko, A. (1994). An Introduction to Mining Seismology. Academic Press.

GA (2018). Confidential consultant's report.

Heidbach, O., Rajabi, M., Reiter, K., Ziegler, M. & WSM Team (2016). World Stress Map Database Release 2016. V. 1.1, GFZ Data Services. https://doi.org/10.5880/WSM.2016.001.

Hudson, J., Pearce, R. & Rogers, R. (1989). Source type plot for inversion of the moment tensor. *Journal of Geophysical Research: Solid Earth* 94 (pp. 765–774).

Jones, R. & Stewart, R. (1997). A method for determining significant structures in a cloud of earthquakes. *Journal of Geophysical Research*: Solid Earth 102 (pp. 8245–8254).

Mercier, J.-P., de Beer, W., Mercier, J.-P. & Morris, S. (2015). Evolution of a Block Cave from Time-Lapse Passive Source Body-Wave Traveltime Tomography. *Geophysics* 80 (2), WA 85–97.

Michael, A. J. (1984). Determination of stress from slip data: faults and folds. *Journal of Geophysical Research: Solid Earth* 89 (pp. 11517–11526).

Niu, F., Silver, P. G., Daley, T. M., Cheng, X. & Majer, E. L. (2008). Preseismic velocity changes observed from active source monitoring at the Parkfield SAFOD drill site. *Nature* 454 (pp. 204–208).

Silver, P. G., Daley, T. M., Niu, F. & Majer, E. L. (2007). Active Source Monitoring of Cross-Well Seismic Travel Time for Stress-Induced Changes. *Bulletin of the Seismological Society of America* 97 (pp. 281–293). https://doi.org/10.1785/0120060120.

Jost, M. L. & Herrmann, R. B. (1989). A student's guide to and review of moment tensors. *Seismological Research Letters* 60 (pp. 37–57).

Tarantola, A. & Valette, B. (1982). Generalized Nonlinear Inverse Problems Solved Using the Least Squares Criterion. *Reviews of Geophysics* 20 (2) (pp. 219–32).

Vavryčuk, V. (2014). Iterative joint inversion for stress and fault orientations from focal mechanisms. *Geophysical Journal International* 199 (pp. 69–77).

Yamamura, K. (2003). Long-term observation of in situ seismic velocity and attenuation. *Journal of Geophysical Research* 108. https://doi.org/10.1029/2002JB002005.