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Seismic Event Location and Source Mechanism Accounting for Complex Block Geology and Voids

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ABSTRACT: An optimized velocity model is an important step towards the goal of accurate and precise seismic results. The assumption of a single or layered velocity model is not always appropriate in examples such as rock volumes that contain complex shaped geological units or large voids. For this reason, this study presents a 3D velocity model method that can be used for source location and source mechanism analysis. Examples from two case studies are presented with the first being an open stope mine, and the second being a block cave mine with 5 geological domains. Using calibration blast data, a significant improvement is shown when the excavation stopes are accounted for in the location velocity model. It is also shown that accounting for the shapes of different geological domains and cave voids produce more accurate raypaths for the seismic energy than from using a single velocity model and straight raypath assumption. This improvement in accuracy is benefiting the integration of seismic results with numerical models and the overall effort to improve the safety and productivity in the rock mechanics industry.

1. INTRODUCTION

Microseismic monitoring is being used daily around the World in a variety of mining, petroleum, and geotechnical applications [1-6]. It is an important method for seeing into a rock mass and quantifying where a certain magnitude range of induced rock fracturing is occurring throughout the volume. The method also allows the mechanics of failure of the microseismic events to be determined.

For mining, high safety and production rate are two essential components for the industry to be successful. Understanding the rock mass response to excavation can be performed in advance by numerical modeling methods and in real time by measurements using a variety of seismic and rock mechanics instrumentation. A good understanding of the geology, rock properties, fault structures and principal stress field is also important. The integration of all of these results can help a mine be safe and productive, while going to greater depths and stresses and utilizing higher yield methods such as block caving. This paper presents results from two case studies utilizing a microseismic system, namely a stope mine and a block cave mine.

2. MICROSEISMIC MONITORING SYSTEMS

Modern microseismic systems consist of sensors and modular acquisition boxes that digitize continuously resulting in no data loss compared to the older style triggered systems. A high speed network is generally used to allow data to be transferred to a central office on surface for real time data analysis, alerting, and visualization. Figure 1 provides an example of this type of system.

Microseismic sensors are recommended to be installed in short boreholes to get past local stress and blast damage zones around tunnels. The main sensors types are geophones and accelerometers. For moderate to strong rock types, in general, accelerometers can record smaller magnitude events than geophones due to their higher frequency range. For softer rock types with higher attenuation, it is recommended to use a lower frequency geophone sensor. Figure 2 shows examples of triaxial and uniaxial seismic sensors.

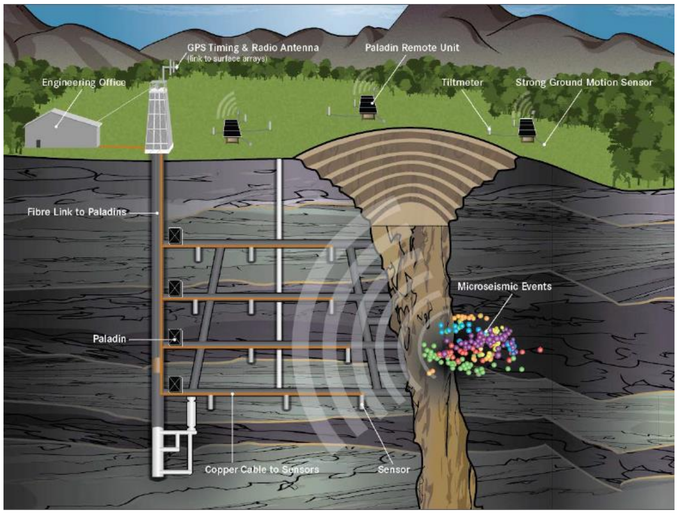

Fig. 1. A schematic showing an example microseismic monitoring system setup.

Fig. 2. Four types of seismic sensors including from left to right: a high pressure borehole triaxial geophone; a triaxial geophone; a triaxial accelerometer; and a uniaxial accelerometer.

The optimal configuration for a seismic system is to have sensors positioned equally throughout a 3D volume. A mixture of uniaxial and triaxial sensors are recommended. Event locations can be uniquely determined using sensors installed in a 2D or 1D array if there is at least one working triaxial sensor in the array. In these two cases, p-wave polarization information is used as well as arrival time data to determine the location. Overall, the highest source location accuracy can be expected for a 3D configuration of sensors.

Figure 3 provides an example of a monitoring system comprising of a mixture of uniaxial and triaxial sensors over a volume on the order of 600x600x600m. An array design analysis has been performed to determine the theoretical location accuracy of a seismic event in different locations over a 3D grid. The array design method uses an estimate of the elastic properties (and variability) of the rockmass as well as other uncertainties in the input parameters to the source location method including elastic wave arrival time accuracy. Figure 3 identifies the 3D isosurface in the mine where 15 meter seismic location accuracy can be expected.

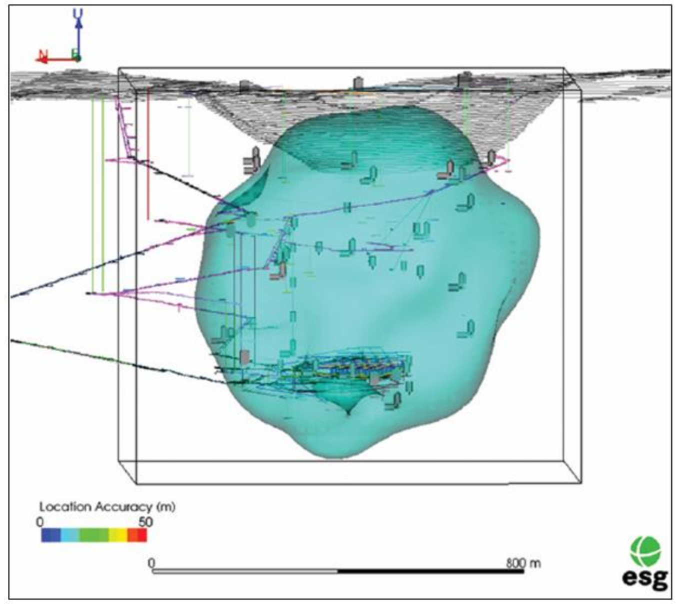

Fig. 3. An example sensor array (small grey cylindrical symbols) and green isosurface showing a specific expected location accuracy (in this case 15m) for the site.

3. 3D VELOCITY MODEL

There are a variety of microseismic event location methods available but a common fundamental parameter for the accuracy of the result is how well the velocity model (VM) used matches the rock mass volume. Figure 4 shows a schematic of a layered velocity model of varying velocity values. The blue lines map the paths of the fastest P-waves from the source to the sensor, and show significant refraction (including critical refraction) at layer boundaries.

The 3D VM used in this paper is based on the work of [7] who present a method for source location using 3D raytracing around an open pit mine with heterogeneous geological units. [7] show how a variable velocity model can be calculated using the Fast Marching Method (FMM) which is an approach to wave front reconstruction proposed by [8]. The algorithm has been further developed by incorporating methods of [9] which provide special treatment for grid cells intersecting a velocity interface and control of the wave front curvature.

The algorithm has been adapted to work with closed low velocity 3D volumes such as a mined stope or cave. The 3D void objects are carefully checked for smooth variation and consistency. The use of parallel computing power allows this type of algorithm to be run in a few hours for a reasonably fine grid. Once the variable velocity model is produced, the final source location is determined within a few seconds using an iterative Simplex location method.

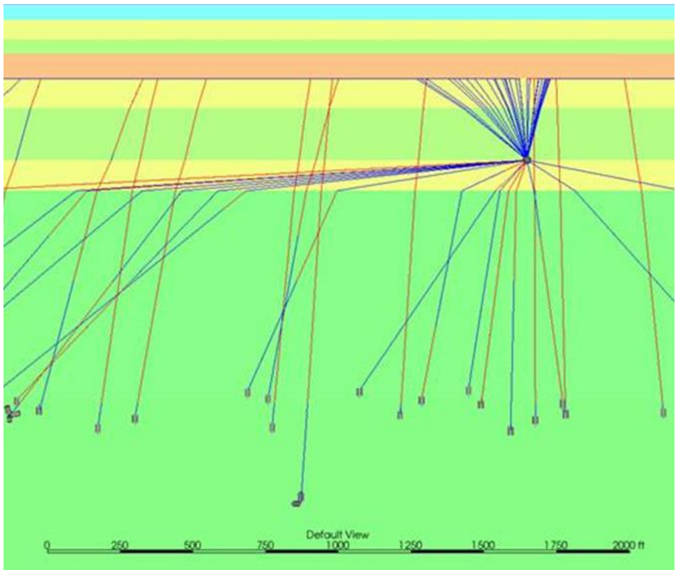

Fig. 4. Lines showing the fast P wave raypaths for a layered velocity model from source (blue dot) to sensors. The site geology is horizontal layered geological units of varying properties (depicted by different colors).

3.1. Source Locations from Case Study 1

Case Study 1 is an underground hard rock mine in North America. Figure 5a shows an example of a known blast location using a single VM being mislocated by 157ft. The main reason for the mislocation is due to the significant excavation voids (colored irregular shaped volumes) in the mine. As expected, the calculated location is further away from the stopes due to the straight raypath assumption in the location method with a single VM and the fact that the fastest raypaths are actually going a longer distance around the voids.

Figure 5b is an example of the same blast being located by only using arrival times from sensors with straight raypaths that do not intersect any of the mined stopes. This approximately halves the location error to 79ft. The issues with this method is that it is not trivial to quickly determine which raypaths are unaffected by the voids, and also that it is not good practice to drop high quality data (high signal to noise) data from a location routine. This is especially an issue for a sparse sensor array or for a small event recorded on only a few sensors. In this case, a location routine can calculate a poor location with an unrealistic small location error since the solution being solved is not significantly over determined.

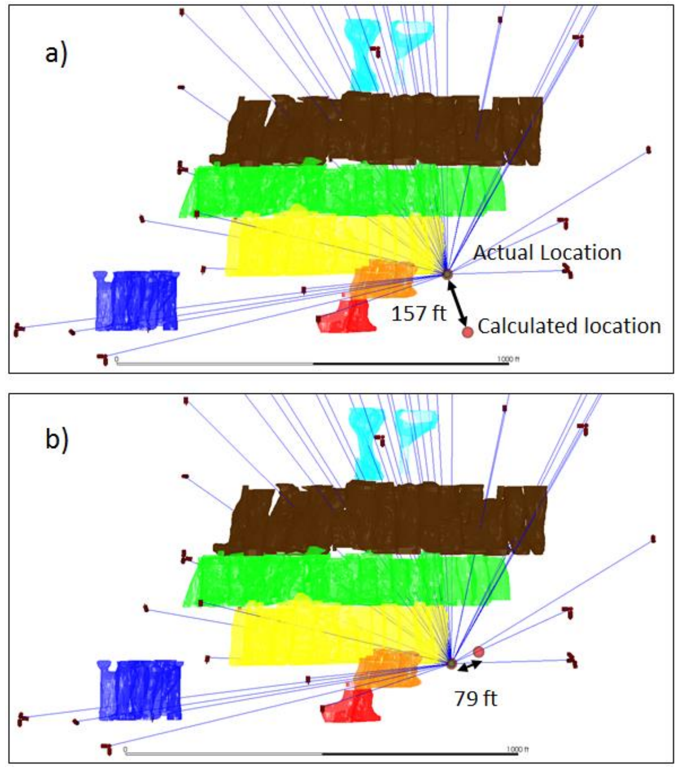

Fig. 5. In (a) the source location of a blast assuming a single velocity model and straight raypaths. In (b) the source location of a blast after removing raypaths that are intersected by mined voids (coloured blocks).

Figure 6 shows the effect that the 3D VM has on time isolines. A single VM would show perfectly circular time isolines radiating from the source. In this example the time isolines from the source are significantly affected by the mined stopes (blue objects) causing slowness over distance.

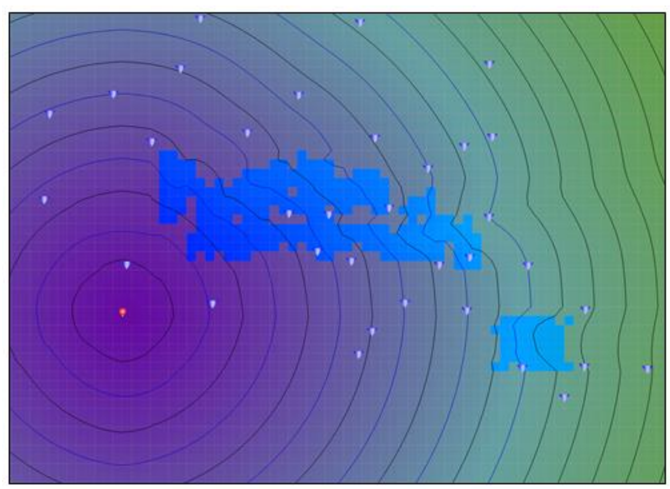

Fig. 6. A 2D section through the volume showing P-wave travel time isolines in black from the seismic source (red dot). The blue features are excavated voids at the Case Study 1 mine. The isolines are seen to deviate significantly as they pass through the low velocity voids.

For Case Study 1, the 3D VM is built and tested on a calibration blast that is mislocating by 59ft using a single VM (Figure 7a). Uses of the 3D VM adjusts the location to within 7ft of the known location which is an 8x improvement over the single VM.

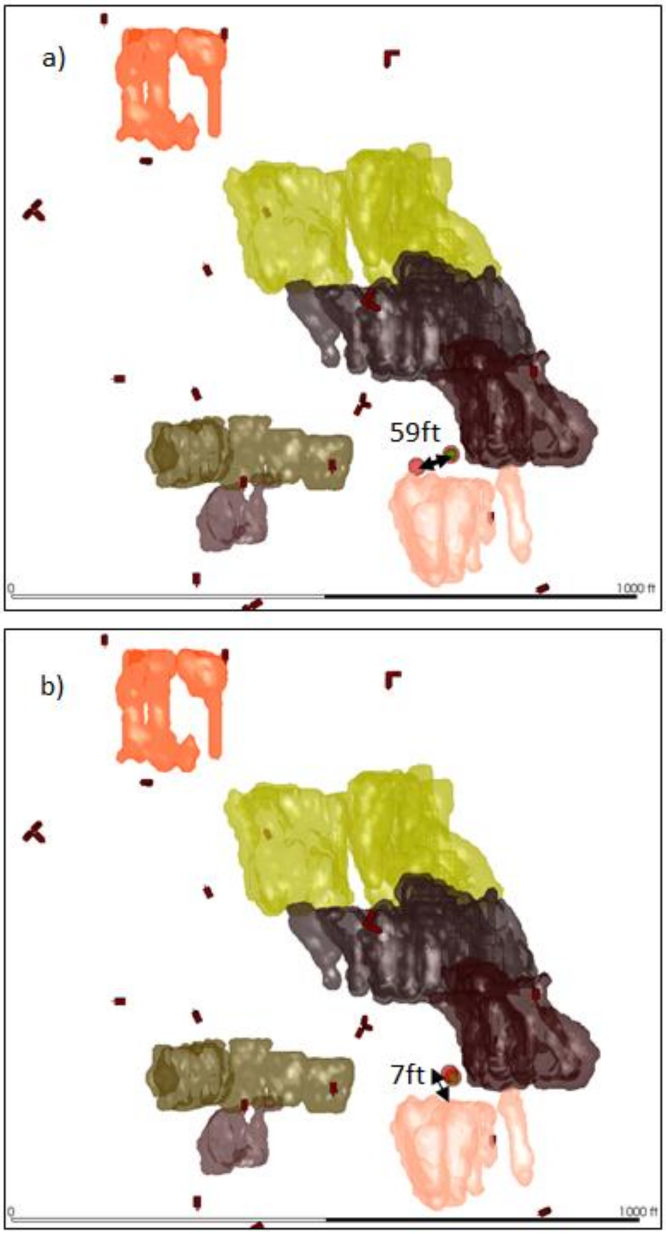

Fig. 7. In (a) the source location of a blast assuming a single velocity model and straight raypaths. In (b) the source location of a blast using a 3D velocity model and ray tracing that accounts for the mined voids (coloured blocks).

The 3D surveys of blast volumes are generally compiled 1-2 months after the finish of blasting, due to the time required to muck, support and complete the surveying. Figure 8 shows how a simple 8 point cubic representation of each mined stope can be used to capture the main volume shape. The idea is that this representation is a way to update the 3D VM as soon as the blasts have occurred, instead of needing to wait until the actual surveying has occurred and then reprocessing the seismic events. Essentially, the design shapes of the stopes planned by the mine engineers can be used to gain the majority of the location accuracy improvement expected from including the void in the 3D VM and location method.

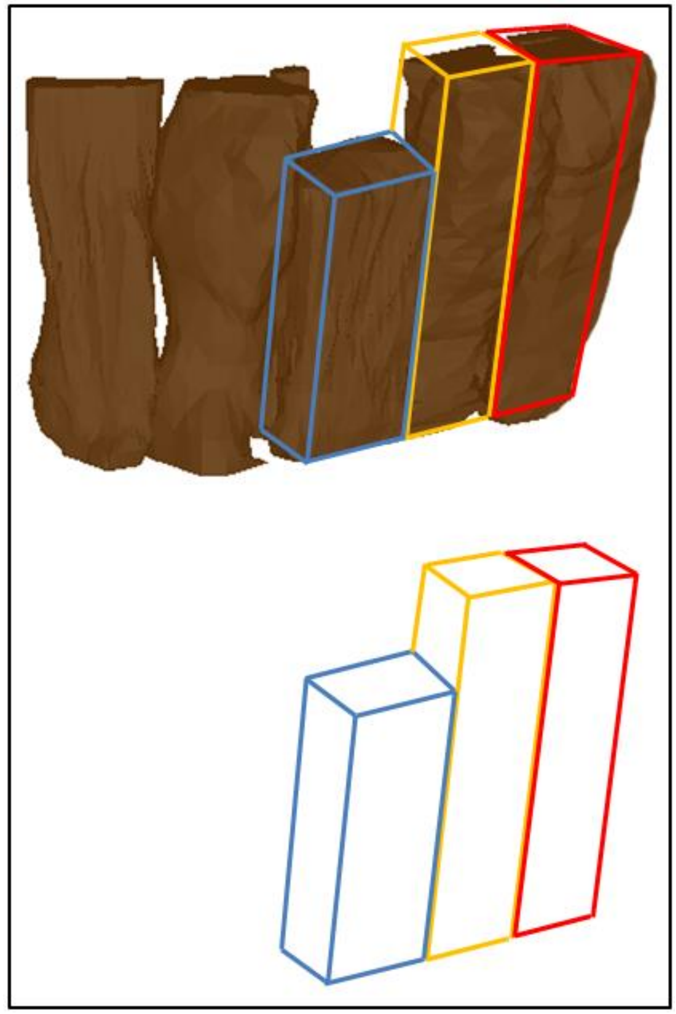

Fig. 8. A simple 8 point cubic representation (blue, yellow, red) of three of the surveyed mined blocks (brown).

3.2. *Source Locations from Case Study 2*

Case Study 2 is a medium strength block cave mine in North America. Figure 9 shows the locations of the seismic sensors as well as calibration blasts with known locations.

A simplified 3D geological CAD model was provided by the mine showing the 5 main geological domains. Figure 10 is a 2D plan section through the geological model showing the shape of each domain to be highly variable and not fitting a layered stratigraphy. Initial P-wave and S-wave velocity values were given to the domains based on a database of laboratory velocity testing on drill cores. Velocity testing of drill core is known to not be an exact representation of rock mass velocity, since the value can be dependent on factors such as sample size, seismic signal frequency, and rock quality [9]. However, the laboratory velocity values identified that the different geological domains had different velocity ranges, with mean values that varied by about 20% which is significant for seismic location. These values were used as a starting point for the development of an optimal variable velocity model.

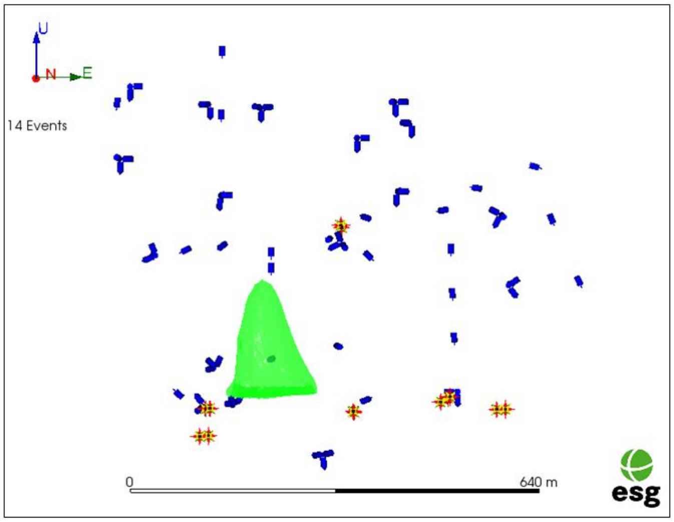

Fig. 9. Blast locations (red/yellow symbols) used for the calibration of the velocity model. A cave profile is shown in green as well as the sensors in blue.

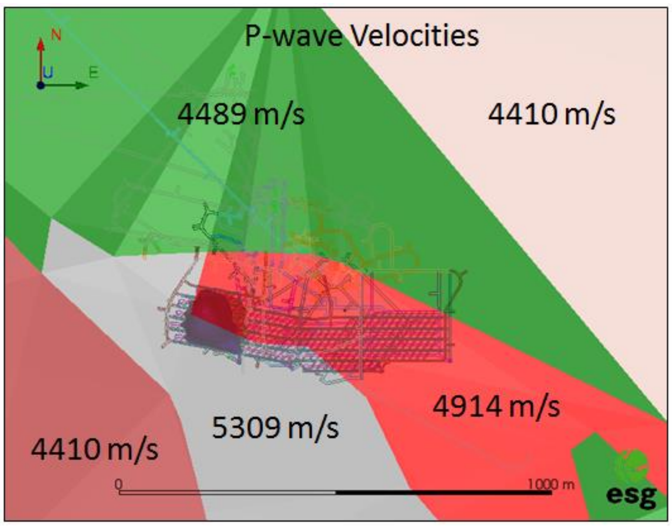

Fig. 10. The optimized P-wave velocity values determined for each of the geological units using the calibration blast data.

Using the optimized VM, the cave profile was added as a void and the full 3D VM determined. Figure 11 shows the time isolines from a blast location. The isolines are significantly affected by the boundaries and properties of the different geological units, as well as the cave void.

Figure 12 shows the fast raypaths of P-waves travelling from an induced event near to the side of the cave void to the seismic sensors. A number of the raypaths are seen to curve and pass around the green void as would be expected due to the faster properties of the host rock.

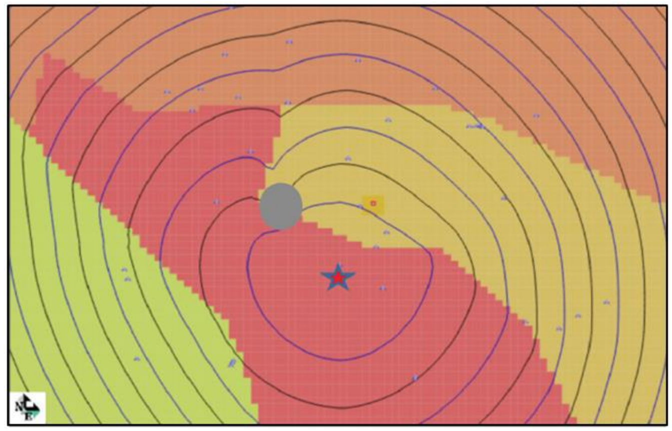

Fig. 11. For a 2D section through the volume, time isolines for a P-wave travelling from the seismic source (star symbol) outwards. The isolines are affected by the 4 geological units shown as well as the cave void (grey circle).

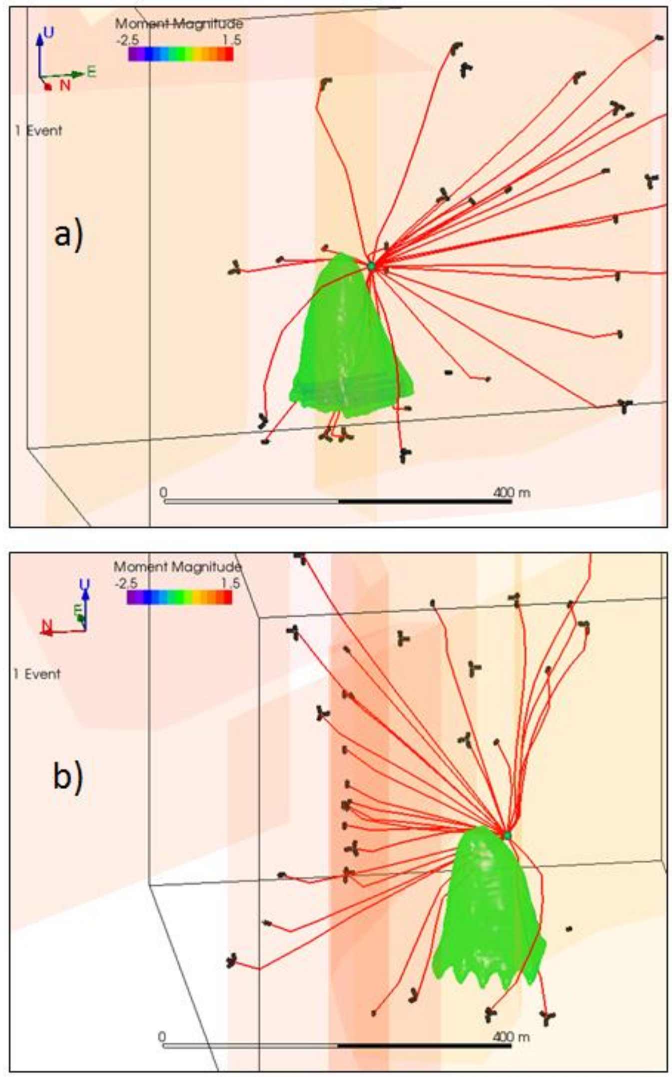

Fig. 12. Two views showing an event (green dot) and the P-wave raypaths (red lines) using the 3D velocity model. Some of the raypaths are seen to propagate around the cave void (large green object), as expected for the fastest wave path.

3.3. *Source Mechanism Analysis*

The seismic moment tensor (MT) method is a powerful way for understanding the mechanics of failure of each seismic event and relating it to the overall rockmass response to excavation. Many studies [e.g. 11, 12] have shown the application of the method to mining and the successful use of both uniaxial and triaxial seismic sensors in the solution.

In this study, source mechanism solutions are calculated using the 3D VM. The MT method is highly dependent on the take off angle of the seismic energy from the event towards each sensor. The use of a 3D VM can change this take off angle significantly. The MT method also requires an accurate distance correction to the amplitude values used. Figure 12 shows the fast seismic energy can travel significantly further distance than the equivalent straight raypath if a void is present in between the sensor and event. Figure 13 shows the MT solution using a 3D VM for the event displayed in Figure 12. The solution uses uniaxial and triaxial P-wave information and shows a solution with good constraint (high R^2 amplitude fit and low condition number).

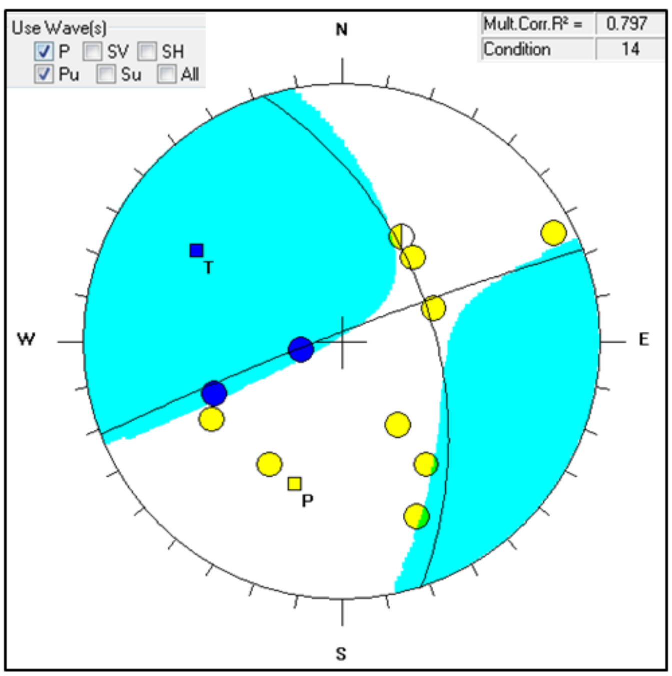

Fig. 13. The source mechanism solution showing data points (blue, yellow circles) on a lower hemisphere stereonet projection. A 3D velocity model is used in the solution that accounts for complex geology and a block cave void.

For events occurring close in space and time, [13] show how the local stress tensor directions can be determined from the source mechanism solutions of mining induced events with no constraints on the failure type. For source mechanism solutions that are dominantly shear failure, there are two possible fracture planes. Using the stress tensor method, the ambiguity can be resolved and used to determine which fracture plane is most likely to slip under the applied stress conditions. Event mechanism solutions can be converted to penny shaped disks that represent the dominant fracture plane. [3] show examples of this type of fracture plane analysis and display for many types of mechanisms including opening, closing and shear. Figure 14 provides an example of this for a group of dominantly shear slip events. The method is a powerful way to visualize a discrete fracture network and help understand the way that distributions of microseismic events are clustering and coalescing together.

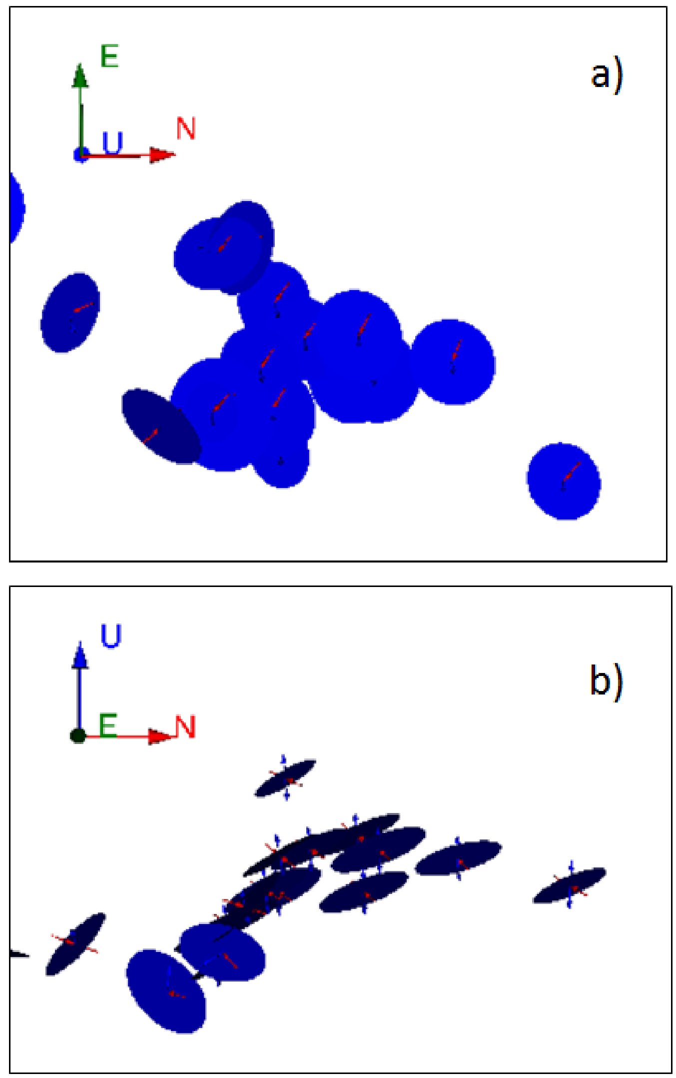

Fig. 14. A cluster of event source mechanisms that have been interpreted for their dominant failure orientation, and displayed as penny shaped disks. The disks are scaled to the seismic source radius.

4. CONCLUSIONS

Microseismic monitoring systems are an important way to see into a rock mass and quantify where stress induced damage is occurring throughout a 3D region.

The accuracy of the microseismic event locations and mechanisms are affected by the type of VM used to represent the rockmass volume. This paper presents examples of mine blasts and events located using a complex 3D VM with multiple geological domains and voids. The 3D VM is shown to more accurately locate compared to a single VM that assumes straight raypaths. The 3D VM has been applied to the source mechanism moment tensor method and shown to produce a well constrained solution. It is suggested that enhanced accuracy in microseismic results can help mine engineers improve mine design, production, ground support and safety procedures by better understanding how the rockmass is reacting to mining activities.

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