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# Use of Seismic Deformation and Stress Inversion Analysis to Help Improve the Understanding of Rock Mass Response to Excavation

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**ABSTRACT:** The rock mass response to mining is a complicated time dependent process that involves elastic and inelastic stress change. For most rock types, a microseismic monitoring system offers a way to see into a volume and accurately identify where inelastic fracture creation, shear movement on faults, or closure type events are occurring. In general mines collect and archive a significant amount of information in a seismic database over time. A closer seismic analysis of data (in addition to location and magnitude) can reveal hidden deformation/failure processes occurring in the rockmass over time, especially when looking at seismic event clusters. This paper presents results from the seismic deformation method and stress inversion analysis applied to seismic clusters from monitoring systems installed in two hard rock mines in Ontario Canada. Seismic deformation projected on a known fault surface is presented as a method for interpreting which region of the fault has failed. Seismic stress inversion analysis is performed on a cluster of seismic source mechanism results as a way to determine local stress directions and stress magnitude ratio in a region of a mine. Seismic stress results offer an important way to help validate numerical stress model results. This paper shows how more advanced microseismic analysis techniques can be used to produce results that can help engineers mine more safely and productively.

## 1. INTRODUCTION

Microseismic (MS) monitoring is a powerful method for listening to a rockmass and determining details about where fractures are developing. It is a type of “big data” since most sites with a system will record between 50-2000 individual triggers per day on 10-100 sensors at 5-10kHz sampling frequency. Additionally the systems let the user go back and analyze longer time periods of data. For example, full blast sequences can be extracted and analyzed to help optimize the subblast time sequencing [1]. The blast sequence analysis can check to see that all subblasts are occurring with expected energy, and not too high PPV (peak particle velocity) to be causing dilution of the ore or possible failure of the support being put in place on nearby access tunnels.

All users want to get accurate seismic event locations from their system. This fundamental parameter is becoming more accurate as sites regularly calibrate and improve the accuracy of the velocity model being used. Example of the use of a 3D velocity model (VM) for a block cave mine with complex geological blocks with different properties and a large cave void was shown by [2] to result in a 47% improvement in location accuracy. Also the move to mixed uniaxial and triaxial sensor systems is a cost effective way to get higher location accuracy since there are more sensors in the ground compared to an equivalently priced full triaxial seismic system.

Microseismic systems can be used in real time to quickly identify dangerous areas in a mine and help with re-entry protocols [3]. Additionally many advanced analysis methods can be applied to subsets of data with goals such as identifying planar features, understanding failure mechanics, or interpreting the effectiveness of destress blasting [3,4].

This paper presents advanced analysis methods applied to microseismic systems installed in two hard rock mines in Ontario Canada which both use stope mining methods. Case Study 1 presents analysis of seismic source parameters from a microseismic system consisting of uniaxial and triaxial accelerometer sensors and focuses on the usefulness of apparent stress and seismic deformation. Case Study 2 presents results of seismic stress inversion using a full 3DVM source mechanism method to understand failure mechanics and the discrete fracture network (DFN) that applies to the event locations recorded by a mixed geophone and accelerometer system.

## 2. CASE STUDY 1

Case Study 1 is an investigation of a region of a hard rock mine with a known fault structure. A total of 196 events in a 300ft wide volume over a 2 week period were accurately processed. Fig. 1 displays the events and groups them into Zone 1 (97 events) along a known fault structure marked in orange and Zone 2 (99 events) which encompass a tunnel intersection east of the fault. Magnitude distribution analysis shows mid range b-values of 1.0 and 1.1 for the two zones indicating a similar mixture of small and medium magnitude events in each zone.

Fig. 2 shows the events scaled in size to moment magnitude Mw and colored to apparent stress. It is interesting to see many events with low moment magnitude but high apparent stress which shows the importance of considering more than one source parameter when analyzing a seismic dataset. Moment magnitude (proportional to seismic moment) is a deformation parameter. In comparison, apparent stress is a measure of stress change at the seismic source with high values indicating high stress or increasing stress conditions. Fig. 2 shows the higher apparent stress regions of the rockmass to be in the Zone 2 cluster, and also at the eastern end of the Zone 1 fault.

Seismic deformation, also known as seismic strain rate, is a parameter that can be calculated at different grid points to provide an analysis of the distribution of deformation over a region. The value is unitless and calculated using Eq. (1) where $\Delta V$ is volume, $\Delta t$ is time period, $\mu$ is shear modulus, and $M_0$ is seismic moment.

$$e_0 = \left(\frac{1}{2\mu}\right)\sum_{events}\left[\frac{M_0}{\Delta V \Delta t}\right] \qquad (1)$$

Fig. 3 presents the seismic deformation on a plane aligned with the fault surface. The bright colors show the region on the fault most affected by the seismic activity with the overall blue zone mapping out the total area of inelastic failure. The seismic deformation parameter provides a way to interpret regions of the fault that may have failed compared to regions of the fault that are locked.

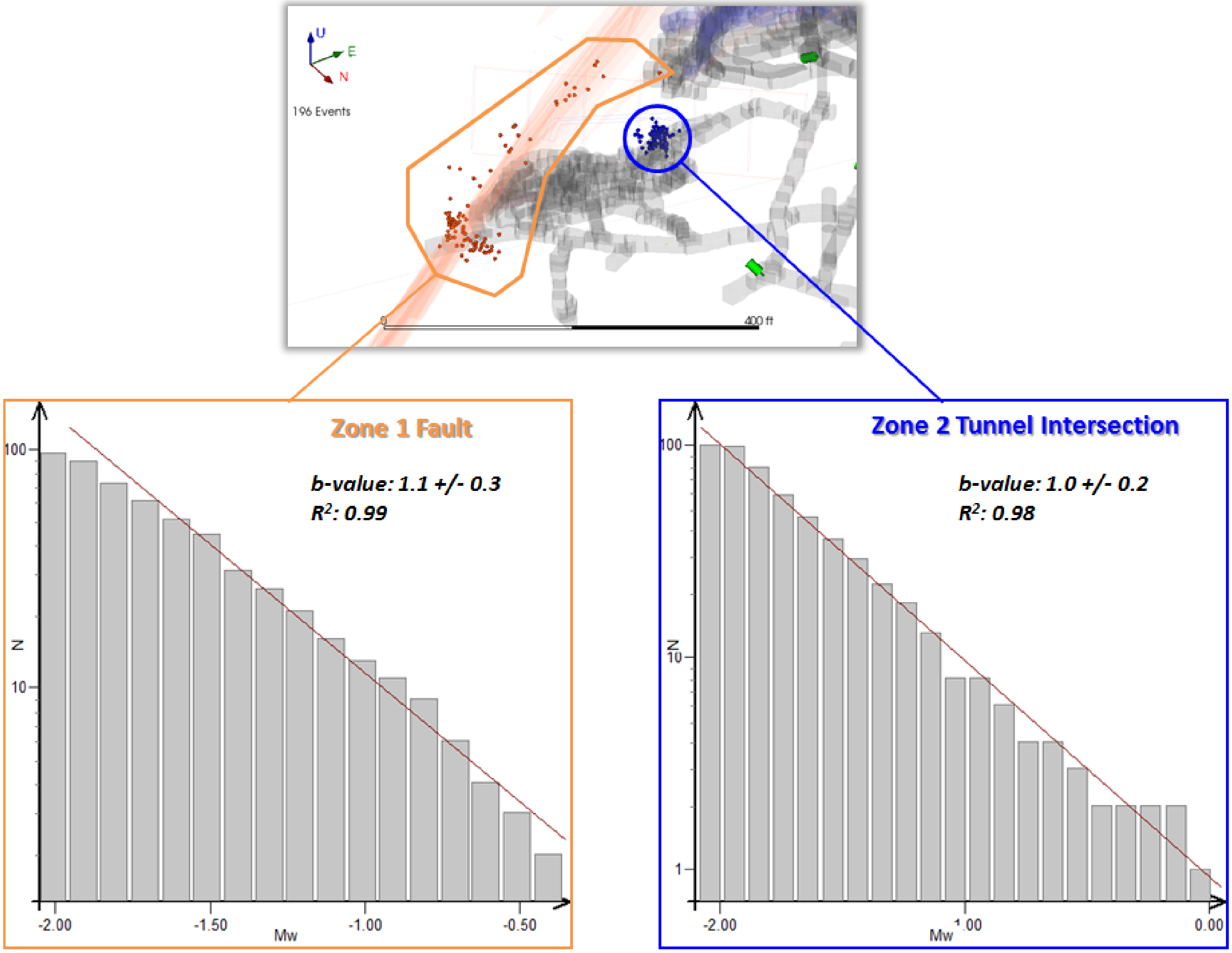

Fig. 1. Microseismic events occurring over a 2 week period for Case Study 1. The data is divided into 2 zones with similar b-values determined for each.

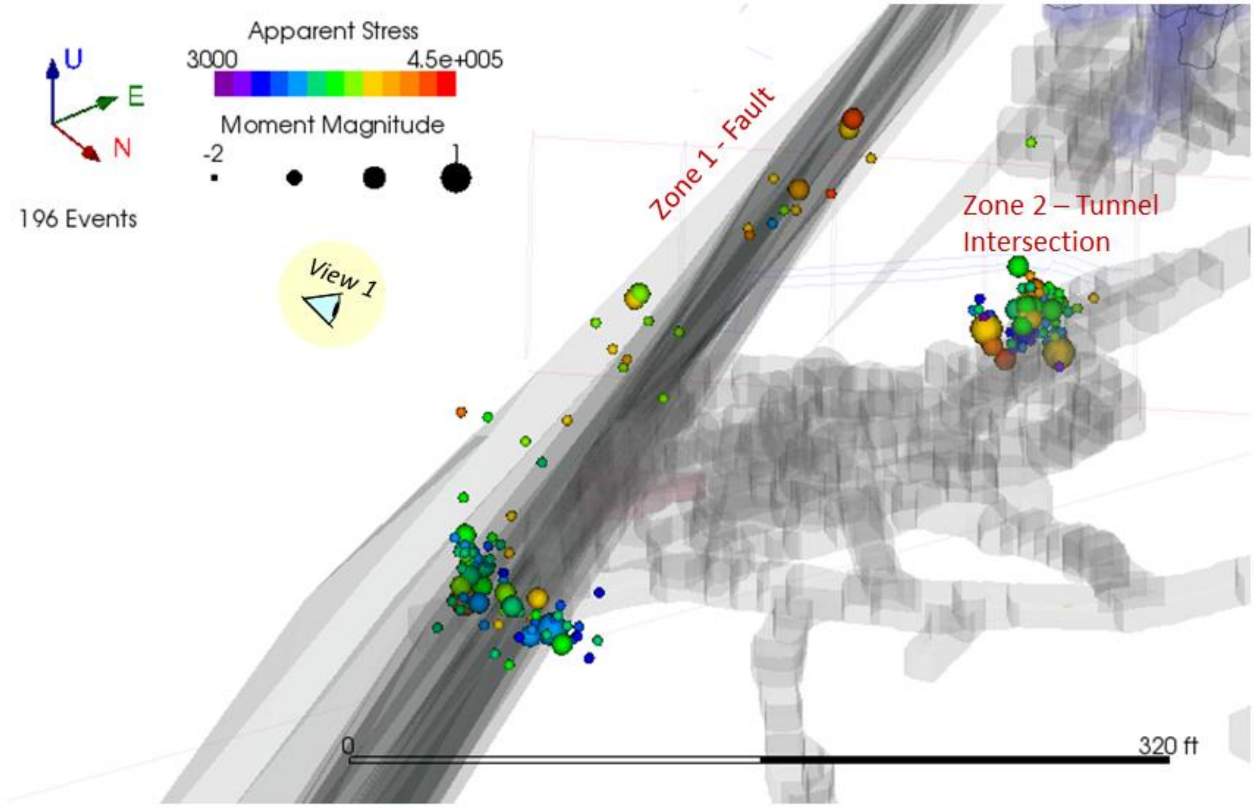

Fig. 2. The microseismic events for Case Study 1 colored to apparent stress and scaled in size to moment magnitude Mw. An increased number of higher apparent stress events are noticed in the east of Zone 1 and in the Zone 2 region.

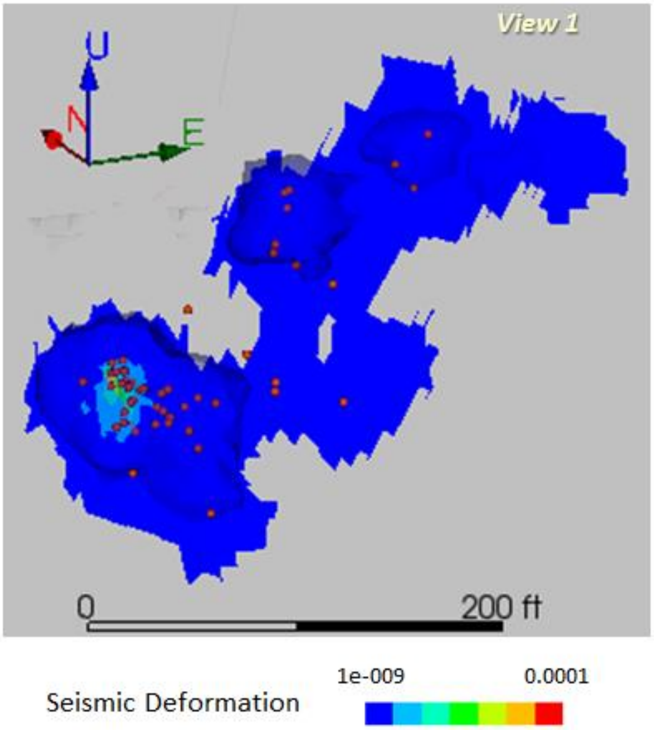

Fig. 3. The seismic deformation projected onto the fault plane for Case Study 1 providing an idea of which region of the fault has experienced inelastic failure. View 1 is the direction defined in Fig. 2.

## 3. CASE STUDY 2

Case Study 2 is a hard rock mine that uses primary and secondary stoping with paste backfill. With time the mining method results in adjacent stopes forming filled voids on the scale of 40m deep, 40m high and 200m long, surrounded by higher strength host rock. Known fault structures are also present which intersect the host rock and ore body.

Fig. 4 compares the location of a -0.7Mw induced event using a 1D VM versus 3D VM with a difference of 24 m determined. The 1D VM assumes isotropy and homogeneity with many of the straight raypaths passing directly through the stopes (Fig. 4a). The 3D VM has P and S wave velocities (1745m/s and 700m/s) for the cement paste filled stopes which are approximately 25% of the host rock values. Fig. 4b shows the raytraced path of the fast energy to bend around the stopes staying in the stronger host rock material as would be expected.

Seismic Moment Tensor Inversion (SMTI) is a well known method for determining the failure mechansm of seismic events [5]. SMTI can provide information on the type of failure (e.g. shear, opening, closure), planar orientation of failure, and overall produces a strain tensor defining the amount and directions of inward and outward strain at the source. The main input data for SMTI is P and S wave first motion (positive or negative) at each sensor, the spectral amplitude of P and S waves at each sensor, and the take off directions of direct energy from the source to sensor.

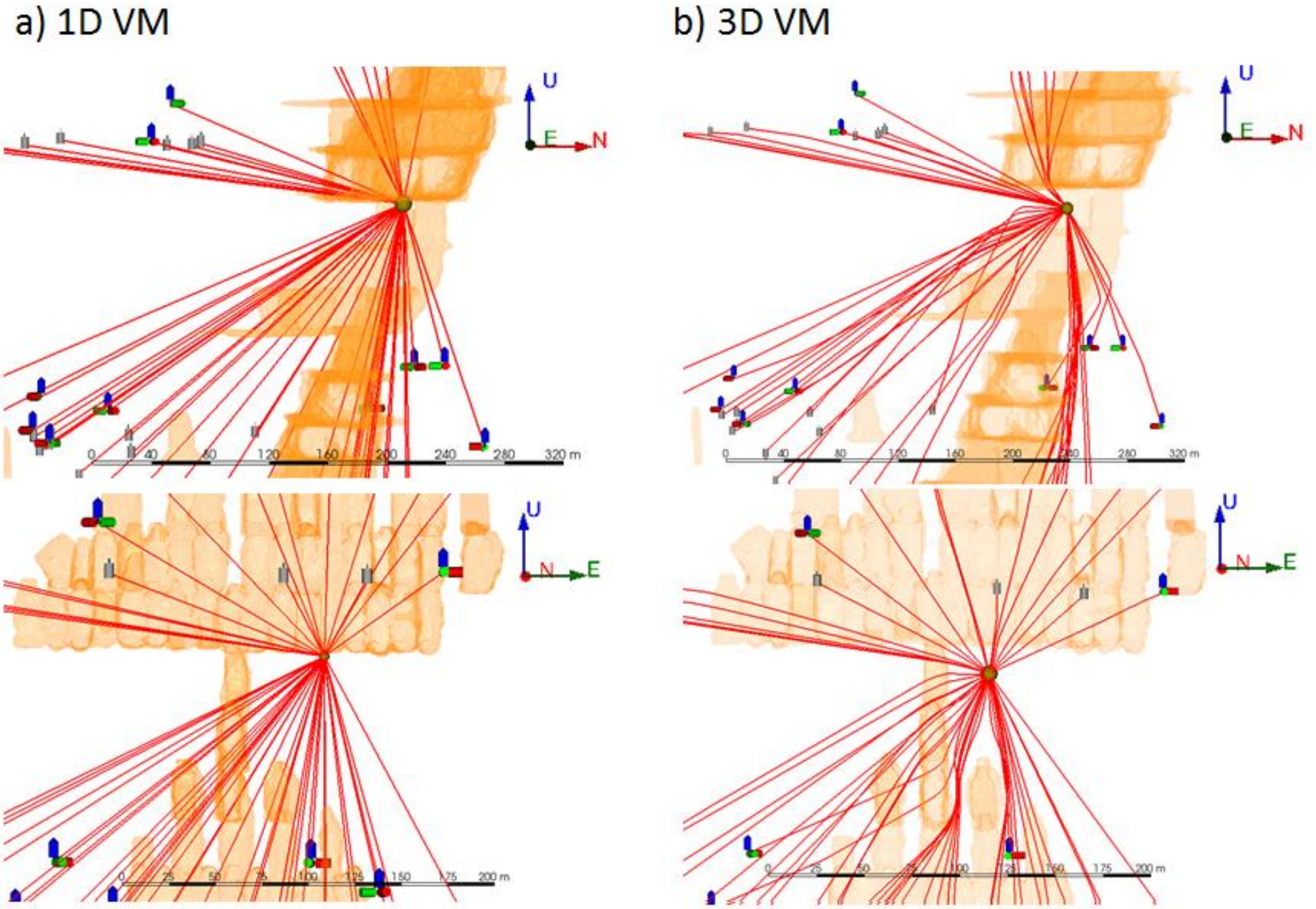

Fig. 4. A -0.7Mw microseismic event occurring in Case Study 2. The event is located in (a) using a 1D VM, and in (b) using a 3D VM, with the location difference being 24 meters. The red lines show the raytracing of the fastest path for the seismic energy and significant bending of some of the rays is seen around the mined out stopes in orange.

Fig. 5 shows the SMTI solution determined for a 1D VM versus a 3D VM. In terms of inversion quality, both solutions have a high $R^2$ value with the 1D VM solution having a slightly higher $R^2$, and both solutions have a low Condition Number for the inversion with the 3D VM solution slightly better. Overall the SMTI solutions have very similar T (tension) axes (in this case the largest positive eigenvalue of SMTI solution) but the P (pressure) axes (in this case the largest negative eigenvalue of SMTI solution) differs by approximately 90° between the 1D VM and 3D VM solutions.

As can be seen in Fig. 4, the take off directions of the red raytraced lines from the event location can vary significantly between the 1D VM and the 3D VM by as much as 30°. As mentioned earlier, the accuracy in take off directions is an important factor for the accuracy of the SMTI solution, and it is believed that the solution showed in Fig. 5e has higher accuracy and confidence due to the 3D VM being used.

Fig. 6 shows a source type plot [6] for 40 3D VM SMTI solutions including the one shown in Fig. 5. A significant number of the solutions are in the center of the plot indicating a dominant shear (DC) mechanism, with the remainder to the left (opening mechanism), and right (closing mechanism). Fig. 7 displays the 40 mechanism results as 'beachball' solutions which helps to see where similar mechanism types are occurring spatially.

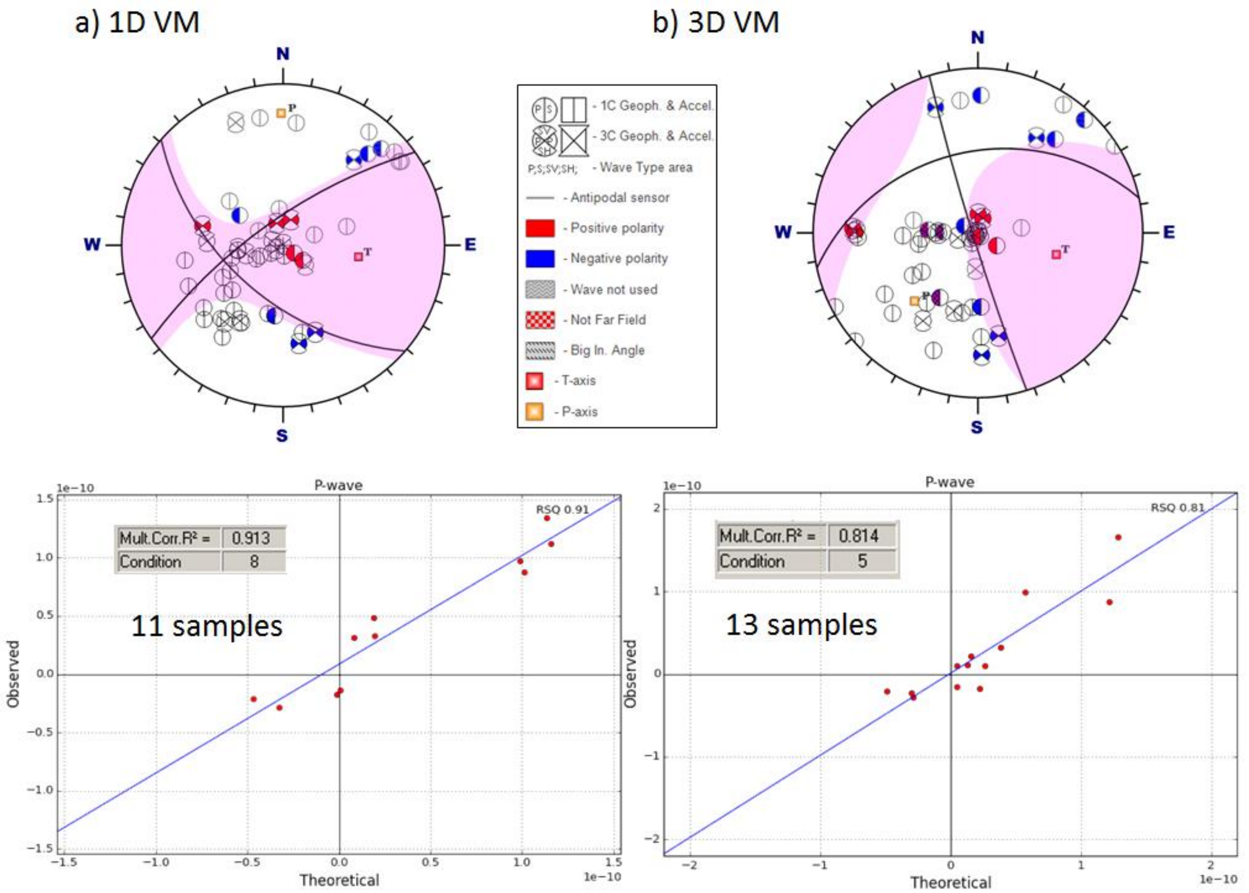

Fig. 5. The SMTI solution for the same event in Case Study 2 using (a) a 1D VM, and (b) a 3DVM. Similarity in the T axis is noticed between the solutions, but a significant rotation by about 90° of the P axis. The take off angles for some raypaths from source to sensor show different positions on the stereonet by as much as 30°.

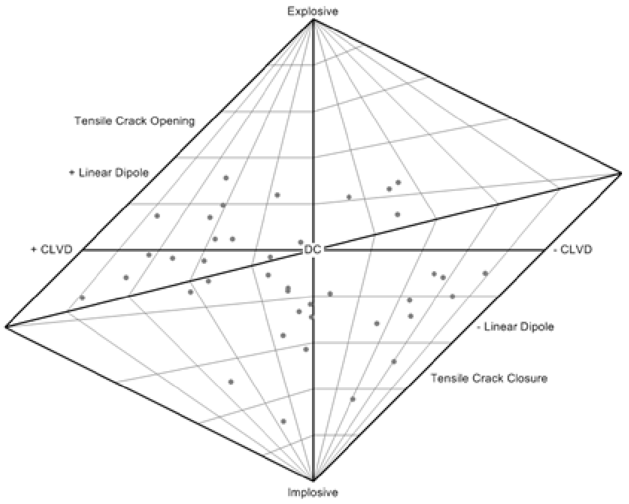

Fig. 6. A source type plot of the 40 mechanism solutions, showing about half of the events are dominantly shear failure while the remainder have significant amounts of non shear failure components.

Seismic stress inversion is a method that can be applied to a cluster of seismic source mechanism results, such as SMTI solutions, to determine four parameters, namely, three angles which define the orientation of the local stress ($\sigma_1$, $\sigma_2$, $\sigma_3$) and the relative stress magnitude ratio $R=(\sigma_1 - \sigma_2)/(\sigma_1 - \sigma_3)$. The resulting local stress tensor is the one that is capable to generate strain tensors that best fit the SMTI solutions. This method is discussed in detail by [7] who made appropriate modifications to the algorithms to be applicable to mining induced seismicity. Specifically the modified seismic stress inversion algorithm of [7] is applicable for source types that include shear failure but also volumetric failure components (opening or closure) which are common in sites that have large openings and voids.

The events in Fig. 7 all occur within a one week period and form a reasonably tight cluster. Seismic stress inversion is applied to the cluster as a whole resulting in an R value of 0.55 and stress directions as given in Table 1.

Table 1. Seismic stress inversion results for Case Study 2.

| | Trend | Plunge |
|---|---|---|
| $\sigma_1$ | 66° | 26° |
| $\sigma_2$ | 221° | 62° |
| $\sigma_3$ | 331° | 10° |

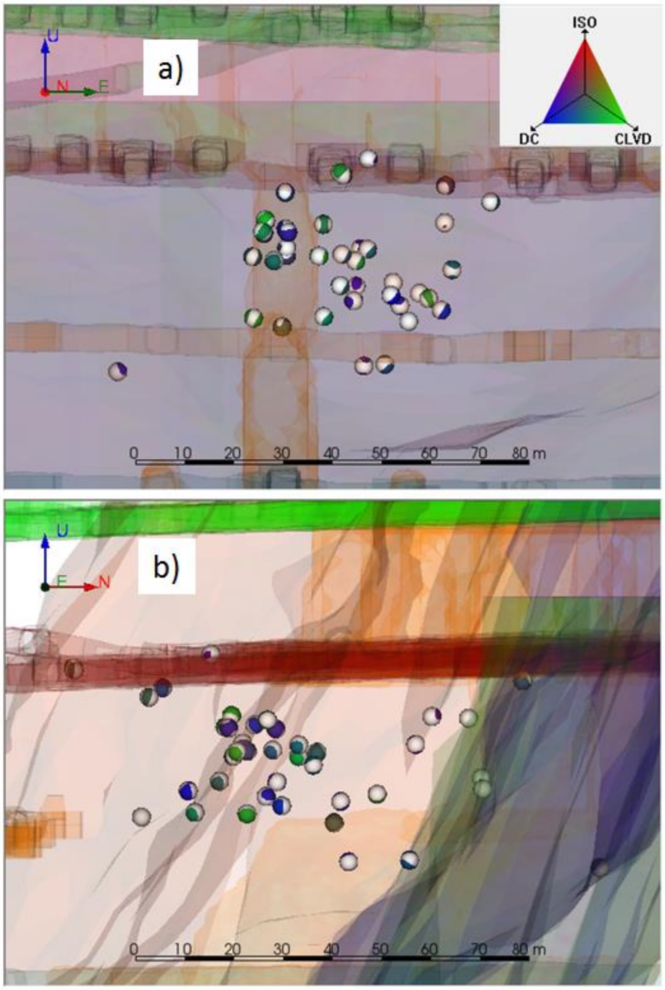

Fig. 7. The 3DVM SMTI solutions for 40 clustered events in Case Study 2 centered about the location of the -0.7Mw event.

Fig. 8 shows the resulting discrete fracture network (DFN) for the 40 events. The DFN is the most probable fault plane for each of the SMTI mechanism solutions based on the seismic stress inversion. Each event is displayed as a penny shaped crack scaled in size to seismic source radius. The DFN is a powerful way to visualize spatially how fractures are oriented and any possible fracture interactions that may be occurring.

Fig. 9 displays the poles of the fracture planes on a stereonet showing there to be two main orientations of fractures planes.

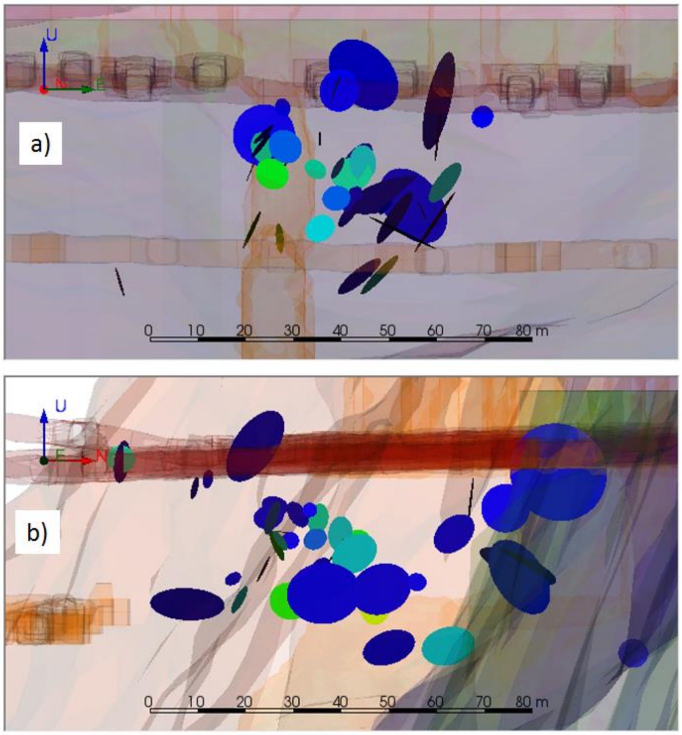

Fig. 8. The discrete fracture network (DFN) comprising of each event shown as an oriented fracture plane scaled to its calculated seismic source radius.

## 4. CONCLUSIONS

Getting the most accuracy and value from a microseismic system are important considerations once a system has been installed and calibrated. The most fundamental result the system can provide are locations of the seismic events as dots in 3D space. However most users expect more from the seismic database results than just location. This paper presents results from analysis methods applied to seismic events recorded in two hard rock mines in Ontario Canada. Case Study 1 shows the use of the seismic deformation parameter and how it can be projected onto a known fault surface to provide an estimate of which portion of the fault has undergone inelastic failure. Case Study 1 also shows how a second source parameter, apparent stress, can be used to interpret varying stress levels in different regions of a rockmass. Case Study 2 showed a 24m improvement in accuracy when using a 3D VM for event location in a rockmass with multiple stope excavations compared to a 1D VM. Additionally the 3D VM SMTI mechanism solution is shown to be significantly different from the 1D VM SMTI solution, due in part to the difference in take off directions for the source sensor raytracing. Seismic stress inversion is performed on a cluster of forty 3D VM SMTI solutions resulting in local stress directions and R value at the center of the cluster to be determined. The authors are currently developing the seismic stress inversion method as a way to provide data to help validation of numerical stress models.

Finally, the seismic stress inversion and SMTI results are used as a way to determine the spatial DFN for all forty events allowing visualization of fracture interaction and identification of two dominant fracture plane orientations. The studies presented show ways that mines can get more out of their seismic systems to help understand rock mass response to excavation.

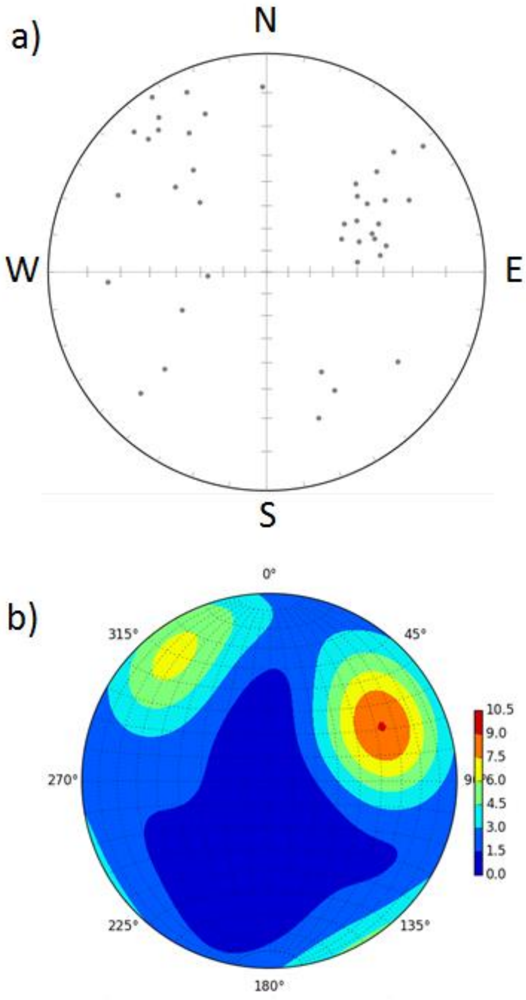

Fig. 9. A stereonet for Case Study 2 displaying the poles of the 40 fracture planes. Two dominant fracture orientations are identified.

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