Large Event Sequence Analysis and 3D Velocity Models for Seismic Event Location Accuracy

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ABSTRACT

Microseismic monitoring is regularly used in the mining and geotechnical industries to provide detailed information about rock mass response to operational activities. This paper implements a variable 3D velocity model (VM) at a North American hard rock mine with the aim of further improving the accuracy of seismic event locations. A collapsing method is also used to help analyse two individual seismic event clusters at another North American hard rock mine. In the first case study, the location accuracy of events is shown to improve by moving from a conventional single VM to a variable 3D VM that accounts for voids and different geological domains. The modal average for the event location accuracy improved from 14 m to 5 m when the 3D VM was used. Additionally, the single VM failed to locate 26 per cent of the seismic events that were located by the 3D VM. In the second case study, the distribution of seismic events was further enhanced by using a collapsing method that highlighted planar structures. The collapsing method was performed on two large event sequences that occurred in close proximity and identified different seismic event distributions. One aftershock sequence aligned along a plane, suggesting an activated structure, while the other large event sequence had a more 3D distribution of events, suggesting a complex stress redistribution on smaller structures.

INTRODUCTION

Microseismic monitoring is widely used in underground mining applications as a tool for better understanding and tracking changes to stress conditions induced by mining excavations. For any seismic monitoring installation, it is important to have an accurate system that can reliably provide the location and magnitude of seismic events. An accurate system provides operators with the confidence to take action when abnormal seismicity occurs. Several factors affect the accuracy of a seismic system, with one of the most important being the similarity of the assumed velocity model (VM) to the rock mass. Other factors include the number of sensors, sensor distribution, sensor type and quality of data processing.

Historically, the majority of seismic systems in the mining industry implement a single VM (homogeneous isotropic VM) that assumes a constant velocity in all directions. The velocity is calibrated from a series of blasts and, ideally, is periodically updated over the life of the mine. However, the actual velocity and seismic wave paths can differ significantly from the assumed direct path of a single VM. In particular, geological variations can result in significant changes to the velocity. The act of mining introduces voids and/or highly fractured zones into the rock mass, which are not taken into account by a single VM. For sites that use an open pit or caving method, a large void is quickly introduced to the monitoring volume, which will have a significant effect on seismic ray paths. In these cases, if a single velocity in all directions is used, the location accuracy will be affected, particularly close to the cave or pit.

It has been possible to include mine excavation voids into microseismic VMs for over half a decade (Trifu and Shumila, 2010). However, due to the increased complexity of the implementation, computationally intensive algorithms and ongoing maintenance requirements, only a few sites have actually implemented detailed VMs. Recent developments in methodology, computational performance and algorithm efficiency mean that the use of detailed VMs is readily and easily available.

There are a variety of advanced analysis methods that can be performed on seismic data once an initial location and the source parameters have been determined. While all steps may have been taken to ensure that an accurate system is installed, a group of located events may still resemble a diffuse seismic cloud, making it difficult to identify any key geotechnical structures. The collapsing method (Jones and Stewart, 1997) is an algorithm that relocates individual events within their error ellipsoids. The algorithm moves neighbours to a common point, which helps to differentiate between random events and a cluster of events on a common structure.

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In this paper, two case studies are presented. The first looks at improved location accuracy of events based on a 3D VM compared to a single VM, while the second analyses two large event distributions using the collapsing method.

MICROSEISMIC ACCURACY – GENERAL IMPROVEMENTS

In general, the accuracy of a microseismic system can be improved by ensuring that the system is well calibrated, expanding the number of sensors or increasing the density of sensors. A main part of a system calibration is making use of a number of seismic sources at known surveyed locations to optimise the rock mass VM. A poor or incomplete calibration will result in higher errors in both location and magnitude, which can impact the usefulness of the system.

The expansion of a sensor array by adding more sensors improves the accuracy of the system in one of two ways. Either the additional sensors are installed in a new location, thereby extending the accuracy of the monitoring volume, or sensors can be added into the existing array to increase the sensor density. A balance between sensor density and coverage of the mining environment can be determined prior to sensor installation by conducting an array design. This ensures a well-balanced system is installed to achieve the monitoring goals of the mine.

The accuracy of a system is also affected by the spatial distribution of sensors throughout the monitoring volume. Certain mining methods restrict access to specific locations. For example, salt and coal mines often mine along a plane with very little perpendicular access to the mine workings. A planar sensor array can result in non-uniqueness. Figure 1a shows a simple 2D model of non-uniqueness. Four uniaxial sensors, positioned in a plane, result in two possible seismic event locations. Figure 1b shows how the directional information obtained from a triaxial sensor can be used to determine a unique solution. A balance between uniaxial and triaxial sensors is recommended at any site. Uniaxial sensors allow for a high-density seismic array to be implemented that provides excellent coverage, location accuracy and detectability. Triaxial sensors resolve the non-uniqueness in planar arrays, but also help with picking S-wave phases and improve the accuracy of source parameter and source mechanism solutions.

CASE STUDY 1 – VELOCITY MODEL IMPROVEMENTS

For sites that contain large voids or zones with heavily fractured rock in the monitoring volume, it is important to have a model that can account for changes in velocity and seismic ray path. A number of studies (Collins *et al*, 2013, 2014a, 2014b; Trifu and Shumila, 2010) show significant improvement in location accuracy by accounting for stope, cave, pit and cavern volumes in the VM.

Case study 1 compares the effect that a single VM and 3D VM have on location accuracy at a North American hard rock mine using the room and pillar mining method. Two distinct geological domains, amphibolite and pegmatite, were added into the 3D VM, along with the mine workings. An iterative process was used to determine the rock velocity in each domain using calibration events.

Figure 2 shows the effect that different geological domains and mine workings can have on seismic travel time. Isolines

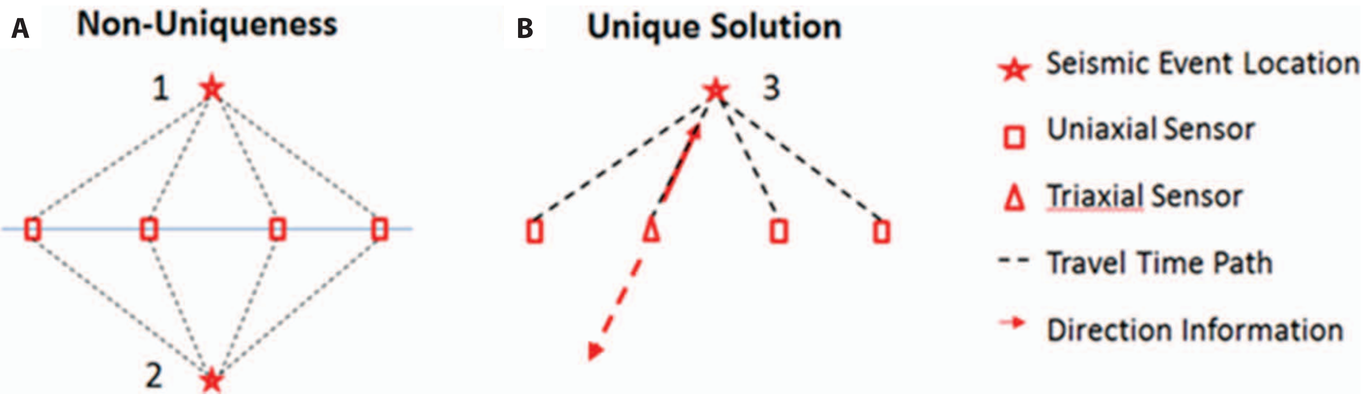

FIG 1 – (A) A simple 2D example of non-uniqueness present for uniaxial sensors in a line (ie there are two solutions for the travel times for an event occurring at location 1 or 2). (B) The directional information from a triaxial sensor combined with the arrival times is able to provide a unique solution (3).

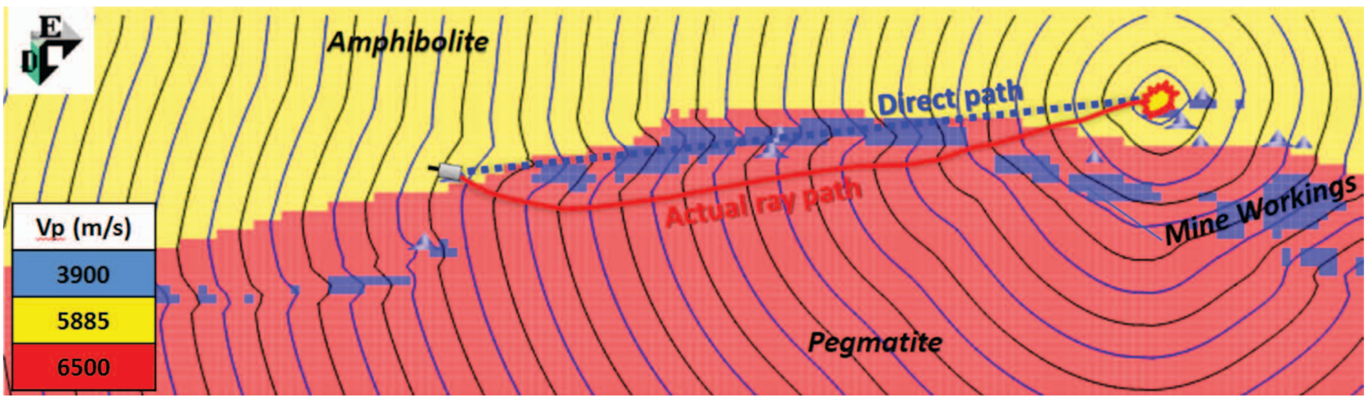

FIG 2 – The effect that different geological domains and mine workings have on the ray path taken from source to sensor. The direct path (blue dashed line) would be the route taken for a single velocity model (VM). The actual ray path (red solid line) is the route taken using the 3D VM.

propagating from a source represent constant travel time and illustrate the effect that the different velocities of the two geological domains and mine workings have on seismic energy. Figure 2 also shows the variation in ray path for a single VM (direct path, dashed line) and 3D VM (actual ray path, solid line), displaying a considerable difference in distance and angle travelled for the two VMs. This difference can have a significant effect on the accuracy of source locations and source mechanism solutions.

Figure 3 presents case study 1 microseismic data from January to June 2014 to compare the accuracy of the single VM and 3D VM. In total, 235 events occurred during the time period with a magnitude range of -3.3 M_W to 1.2 M_W. A general filter was applied to both VMs that removes events with poor location accuracy (>30 m) or those that use less than five sensors. All events processed using the 3D VM fell within the general filter threshold, whereas only 174 events passed the filter threshold using the single VM. Figures 3a and 3b show that there was a significant reduction in the location error from 14 m (mode) to 5 m (mode) when the 3D VM was used. Visual inspection of the event locations in Figures 3c and 3d show tighter clusters in general for the 3D VM results. The lower location error and tighter clustering from the 3D VM gives the mine operator more confidence in concluding where the activity is occurring and making decisions for safety and production based on these spatial regions.

CASE STUDY 2 – STRUCTURES IN SEISMIC DATA

Case study 2 analyses two large seismic events and their aftershock sequences at a North American hard rock mine using the stoping method. The two events occurred three months apart but had a similar magnitude and occurred in a similar location (within 100 m of each other) in the mine. The large events produced very different seismic event distributions.

The location distribution of a seismic sequence can provide useful information about the events and their possible mechanisms. The magnitude time distribution of the two event sequences is shown in Figure 4. For both sequences, the large events occurred at around 11.30 am and triggered an increase in seismic activity that decayed with time. The first sequence, shown in Figure 4a, resulted in significantly more seismic activity than the second. After about five hours, a mid-size 0.3 M_W event occurred with a lower rate of aftershock activity. The second event sequence, shown in Figure 4b, did not trigger a mid-size magnitude event and also resulted in less than half as many seismic events. The difference in the amount of seismic activity and the distribution of the seismicity is interesting considering the events were of similar magnitude (1.2 M_W and 1.3 M_W respectively) and occurred in similar locations in the mine.

The seismic event distribution for the first large event sequence is shown in Figure 5. The events are scaled to their individual errors (by using 3D error ellipsoids) and colour-scaled by magnitude. The events with the largest ellipsoids have the highest uncertainty, while the events with the smaller ellipsoids can be considered the most accurate. The large 1.2 M_W event can be seen in the centre of the image with a small red ellipsoid (high accuracy). It can be quite difficult to identify what is occurring in a seismic event cloud, so further analyses and methods are used to simplify the data. Implementing the collapsing algorithm may identify planar features in the data, which could be interpreted as geological structures.

The results of the collapsing analysis performed on the first large event sequence are shown in Figure 6. A strong planar feature is seen that is centred around the large event at the

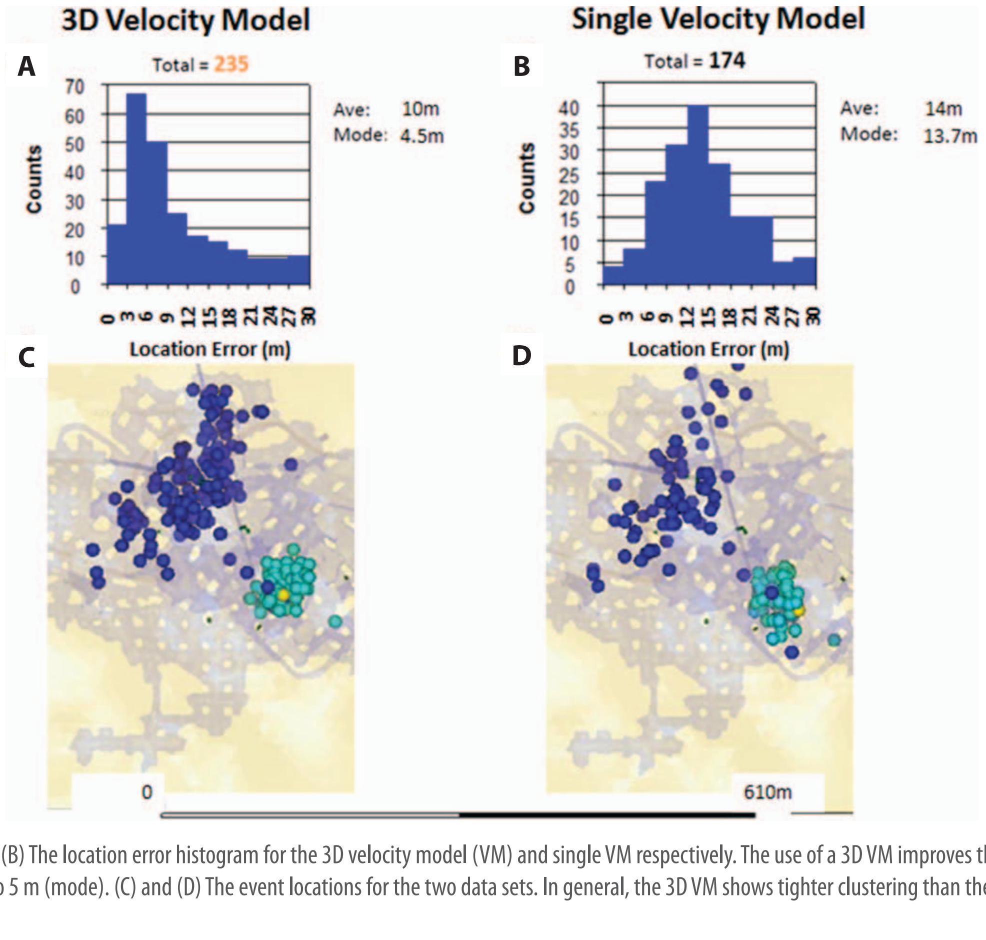

FIG 3 – (A) and (B) The location error histogram for the 3D velocity model (VM) and single VM respectively. The use of a 3D VM improves the error from 14 m (mode) to 5 m (mode). (C) and (D) The event locations for the two data sets. In general, the 3D VM shows tighter clustering than the single VM.

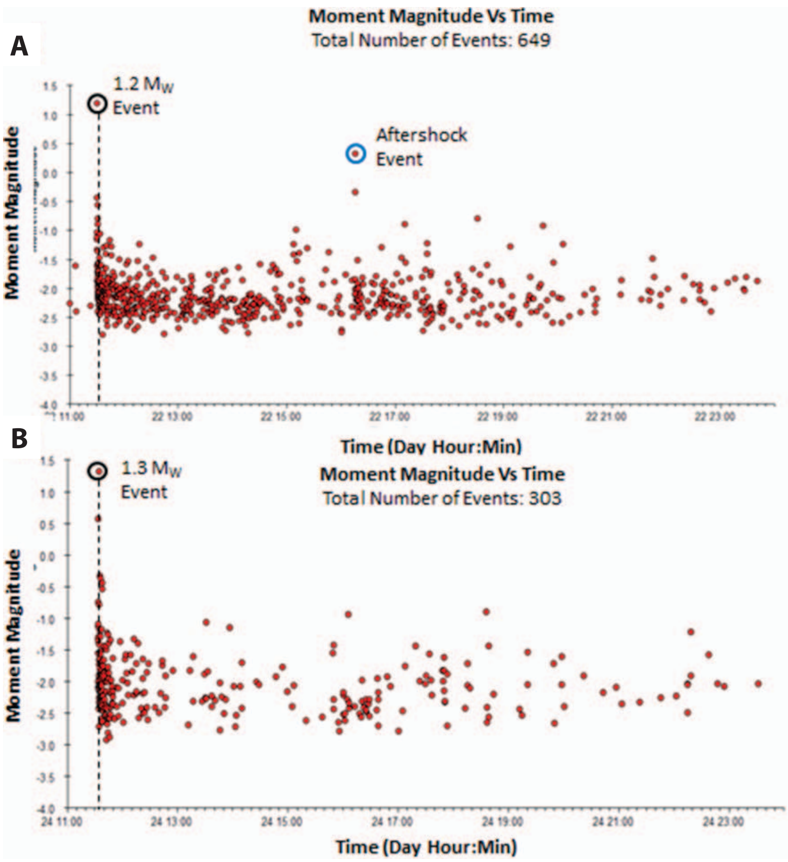

FIG 4 – (A) The first seismic event sequence following a 1.2 M_W event that happened at 11.30 am. A significant increase in seismicity occurs immediately after the event and decays with time. Approximately five hours after the initial event, an aftershock event of magnitude 0.3 M_W occurred. (B) The second seismic event sequence following a magnitude 1.3 M_W event, which also occurred around 11.30 am and resulted in fewer events.

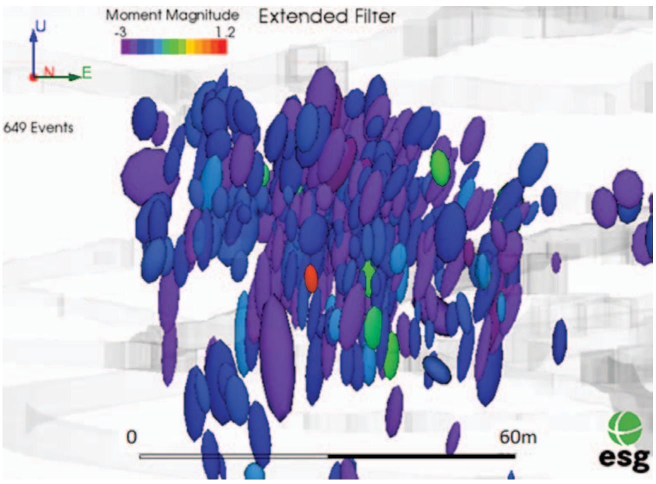

FIG 5 – The error ellipsoids for the first large event sequence. Identifying linear or planar features in the seismic event cloud is not easy due to location errors and the spread of seismicity.

centre of the main cluster. The planarity of the collapsed data and the presence of an aftershock event, which are regularly seen in earthquake seismology, support the hypothesis that an existing structure has been activated. The mid-size aftershock event is likely a further slip phase on the same structure triggered after the first main slip as the stresses redistributed over a five-hour period. Visual inspection of the data indicated the orientation of the planar structure as 63° strike and 45° dip. The Hough transform (Duda and Hart, 1972) is a more quantitative statistical method that can be used to fit a plane to the seismic data, as used by Trifu and Shumila (2014).

The second large event sequence resulted from two large events of magnitude 0.6 M_W and 1.3 M_W. The events were separated by 25 m and occurred at similar times. The large events also occurred around 11.30 am and resulted in an increase in seismic activity immediately after they occurred. The seismic event distribution is scaled to their error ellipsoids in Figure 7.

The collapsing algorithm was also applied to the second large event sequence, and the results can be seen in Figure 8. The events are relocated into linear formations that vary in direction. There is little evidence of planarity in the data, suggesting that a larger fault type structure was not associated with this event sequence. The event cluster is a more 3D distribution of activity, which may be related to the activation of smaller joint sets and stress redistributed around voids.

CONCLUSIONS

Improving the location accuracy of microseismic events by implementing a VM that accounts for different geological domains and mining voids is viable for many mining methods. Collins *et al* (2014a) applied a variable 3D VM at a stope mine as well as a block cave mine and identified significant improvements in overall event accuracy. Collins *et al* (2014b) also successfully implemented a variable 3D VM in a solution mining case with bedded geology. In case study 1 of this paper, a variable 3D VM was applied to a North American hard rock mine that uses the room and pillar mining method. The 3D VM was shown to improve the modal average of the event location accuracy from 14 m to 5 m compared to the single VM. Additionally, the use of the 3D VM located significantly more events than the single VM. It is also

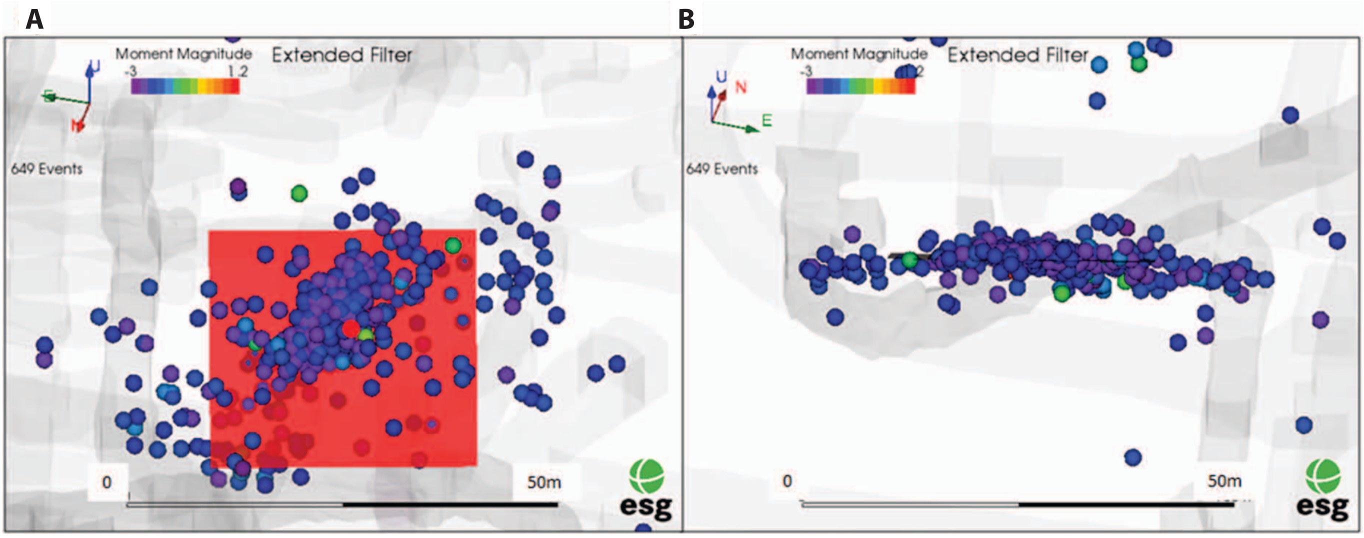

FIG 6 – The results of the collapsing analysis on the first seismic sequence. A planar feature striking 63° and dipping 45° is highlighted by the red plane. (A) Looks perpendicular to the plane. (B) Looks along the dip direction.

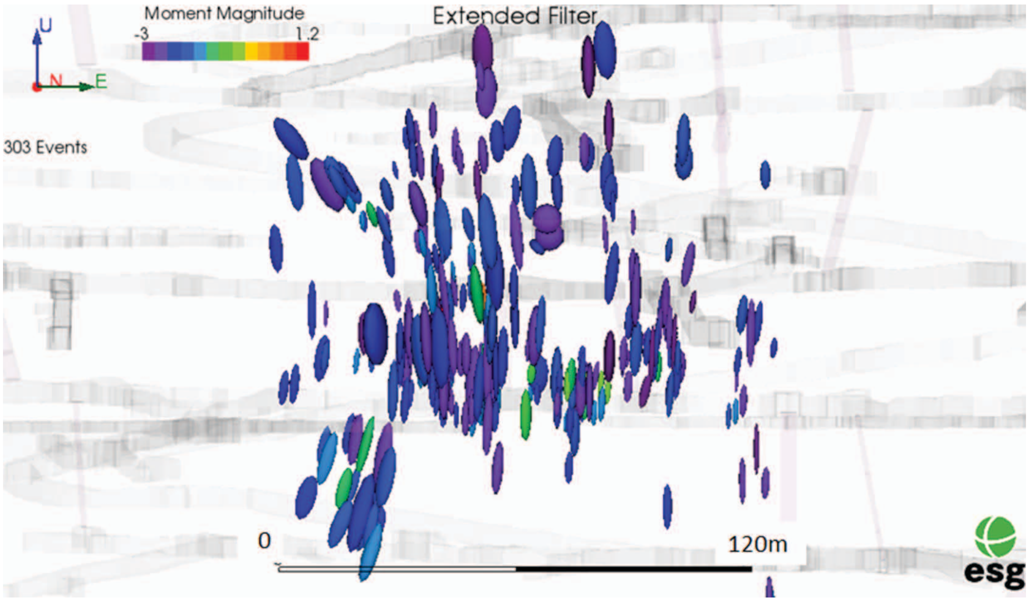

FIG 7 – The seismic distribution of error ellipsoids for the second large event sequence

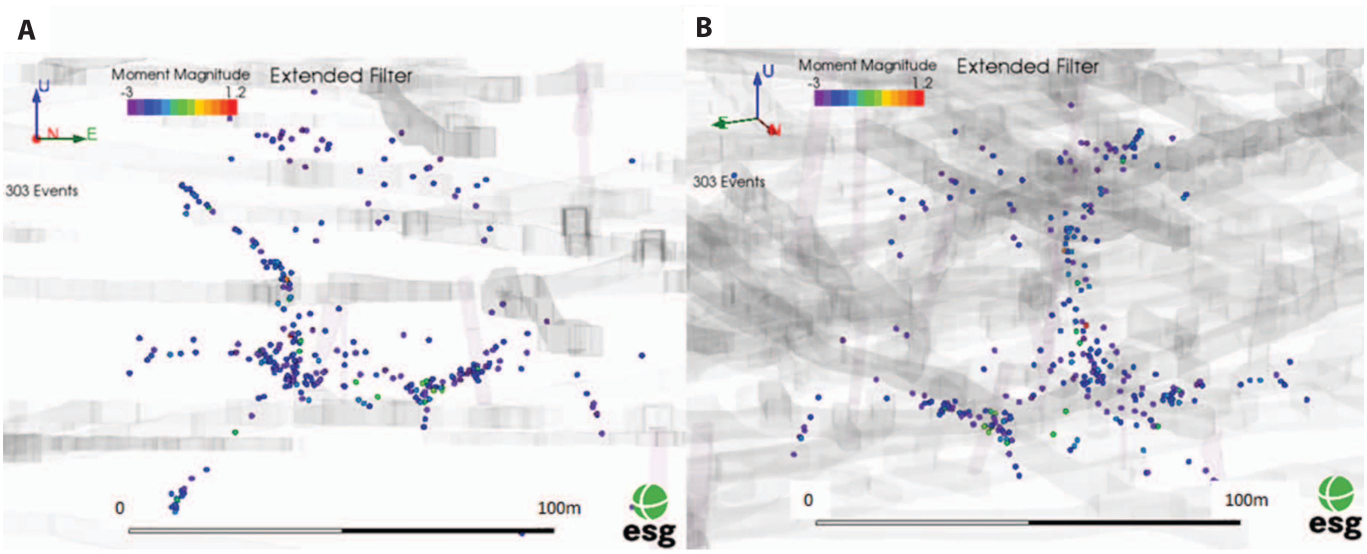

FIG 8 – Collapsing performed on the second large event sequence. (A) Looks northing. (B) Shows a perspective view. Little evidence is present to suggest a geological structure was activated.

important to note that implementing a variable 3D VM is important when conducting source mechanism analysis since the method requires accurate ray paths and take-off angles from the source to the sensor.

Case study 2 analysed two large event sequences at a North American stoping mine. The two large events occurred three months apart but were similar in magnitude and location in the mine (within 100 m) and occurred in a region of similar seismic detectability. Applying a collapsing method to the first large event sequence resulted in a distinctly planar feature that could be quantified as having a strike at approximately 63° and dipping 45°. The strong planar feature may be interpreted as a fault structure. A mid-size 0.3 M_W magnitude event occurred five hours after the main event, which could be interpreted as further slip on the fault as temporal stress redistribution occurred. The second large event sequence produced less seismicity than the first large event sequence, even though it was slightly larger in size. Collapsing of the seismic data cloud resulted in a more 3D distribution with multiple linear features but no planar structures, suggesting different source and structural characteristics. The second large event sequence was likely a redistribution of stress on smaller structures over a 3D region, while the first large event sequence can be interpreted as the activation of a larger geological structure such as a fault in the rock mass.

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