

Use of Microseismic Monitoring Data as an Aid to Rock Mechanics Decision Making and Mine Design Verification

Simser, B.

Sudbury Integrated Nickel Operations, A Glencore Company, Sudbury, ON, Canada

Deredin, R., and Jalbout, A.

Sudbury Integrated Nickel Operations, A Glencore Company, Sudbury, ON, Canada

Butler, T.

Engineering Seismology Group (ESG), Canada Inc., Kingston, ON, Canada



Copyright 2015 ARMA, American Rock Mechanics Association

This paper was prepared for presentation at the 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 28 June-1 July 2015.

This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers. The material, as presented, does not necessarily reflect any position of ARMA, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of ARMA is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 200 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgement of where and by whom the paper was presented.

ABSTRACT: Case studies are presented from Glencores' Fraser Copper, Fraser Morgan and Nickel Rim South Mines showing how microseismic monitoring data can be used as an aid to rock mechanics decision making and design verification. At Nickel Rim South and Fraser Morgan, examples of how recorded development blasts can be used to quickly evaluate source location accuracy and infer the state of rockmass conditions are given. Examples are given as to how network sensitivity can enhance the understanding of the rockmass response to mining are also presented and a case is made for 3D velocity models and recognizing the impact of waveform attenuation from raypath effects, and yielded rockmass conditions. At Fraser Copper, a case history shows how seismic information was useful for evaluating the performance of a successful longhole destress blast that was performed when face-bursting was encountered during a planned underhand extraction of a highly stressed remnant.

1. INTRODUCTION

Glencore's Sudbury Integrated Nickel Operations includes three underground operations, the Nickel Rim South Mine, Fraser Copper Mine, and Fraser Morgan Mine, all located near Sudbury, Ontario, Canada (Figure 1).

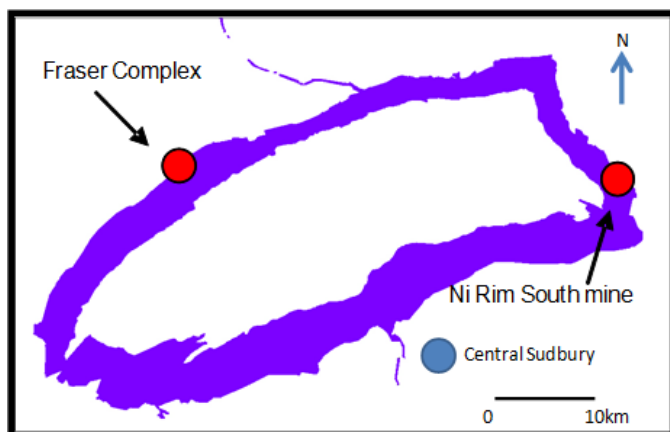


Fig. 1. Simplified plan view of the Sudbury Basin. The Fraser Complex is located near the village of Onaping, and the Nickel Rim South Mine is located just past the municipal airport near the village of Skead.

Fraser Morgan is a nickel deposit accessed via the Fraser Copper Mine infrastructure. Close to 2 million tonnes per year of ore are mined underground from all operations, with Nickel Rim South providing the majority of the material at 1.3 Mt/year.

All three operations are hard rock mines, with excellent rockmass quality. The depth of mining is sufficient to develop pervasive stress fracturing around most openings (Figure 2).

Mining induced seismicity occasionally causes stability problems in the form of rockbursting or seismically induced falls of ground. Although the incidents are rare, the potential safety impact can be large. Seismic monitoring has become the main geomechanical tool to track and understand the rockmass response to mining, and to provide short term feedback for blasting and large seismic events.

All three mines deploy seismic monitoring systems provided by Engineering Seismology Group Canada Inc. (ESG), based in Kingston, Ontario, Canada. The gradual expansion of mining is managed by incremental additions/improvements to each of the seismic arrays.



Fig. 2. (a) Example of stress fracturing caused by high stress revealed after extending an opening from 10m to 16m, 1480m below surface. A section view schematic indicating fractures visible in sidewall is shown in the top right corner. (b) Stress fractures visible when benching the floor of an excavation.

The different states of the seismic systems installed at each mine provide an opportunity to show the value added from different levels of data quality, and the improvements made by deploying dense arrays with wide dynamic range. Some thoughts on improving future seismic system installations to get better spatial coverage earlier in the life of a mine are discussed.

1.1. Nickel Rim South Mine

Nickel Rim South Mine is a primary/secondary blasthole mine which is relatively deep (1100 to 1710m below surface) with horizontal stresses approximately 1.6x vertical. The mine has a complex system of faulting and variable geology, but generally high quality rock. Nickel Rim South Mine has the inherent advantage of being a relatively new mine (first stoping in 2009) where the seismic system was planned from the early stages. For example, fibre optic communications were established at every electrical substation from the initial project phase. As a result, a very dense microseismic array was installed early in the mine life, providing useful information for ground control engineers to evaluate the rock mass response to mining. A short case history is provided showing how recorded development blasts are used to gauge rockmass conditions.

1.2. Fraser Copper Mine

The Fraser Copper Mine is a narrow vein deposit mined using a mixture of mining methods. Most of the historic production has been mined with overhand cut and fill. The vein orientation can be erratic with an overall dip of 45° with local rolls going from horizontal to vertical. The steeper veins are usually extracted with blasthole methods, especially in sill pillar areas. Flat veins are mined with drift and fill methods. The Fraser Copper Zone is below the historic Strathcona Mine which operated in the late 1960's until the late 1980's, with the narrow vein mining starting in the early 1980's. The seismic communication infrastructure has been more of a challenge, with fibre optic only being made available for seismic monitoring in the last few years. The original backbone of the system was via copper cable to surface.

High stress remnant extraction of intermediate dipping veins has proven to be a significant challenge at Fraser Copper. The squat nature of the narrow vein sill pillar can hold very high stress until the very late stages of extraction. A case history showing the performance of a planned underhand extraction of a highly stressed remnant is given. Face bursting necessitated a change from the mining plan and a successful long hole destress blast was conducted. The performance of the destress blast, as well as the overall rockmass response to mining in this area is presented using microseismic data and underground observations.

1.3. Fraser Morgan Mine

The Fraser Morgan Mine is a blasthole nickel mine offset a few kilometers from the narrow vein Fraser copper mining and is accessed via the same shaft system. It has a separate seismic array which monitors activity from two distinct mining zones between 1000 and 1500m below surface. The array first started recording events in May 2013, and has been incrementally expanded as mine development has progressed. In essence, the mine seismic coverage varies considerably due to practical implementation and logistical issues. Areas of poor coverage are gradually being addressed, but uniform coverage across the three mines is not currently possible. A short case history is shown using recorded development blasts to gauge rockmass conditions in a similar fashion to the analysis performed on Nickel Rim South data.

2. NICKEL RIM SOUTH MINE

Nickel Rim South Mine started stoping operations in May 2009, and the early version of the seismic monitoring program started in January 2009. The seismic array includes a mixture of uniaxial accelerometers and 15 Hz triaxial geophones. The geophones were incrementally added starting in 2010 to provide improved dynamic range. The uniaxial accelerometer array quantifies seismic moment accurately from moment magnitude -2.0 to -0.5. For events with magnitude > -0.5, the calculated energy and moment are known to be underestimated due to the lack of low frequency response from this specific type of accelerometer (Figure 3). Data from 2010 for the blended sensor array is shown in Figure 4. The overall linearity of the power law distribution (Gutenberg-Richter relation) is improved above moment magnitude -0.5. The 15 Hz geophones capture lower frequency information which significantly contributes to the moment magnitude estimate for larger seismic events.

Although there may be other possible explanations for the deviation from linearity when plotting the log cumulative number of events versus magnitude, the assumption is that deviations are due mainly to inadequate seismic moment estimates. Recorded blasting events will, for example, deviate from the power law distribution relative to rock fracturing or structural slip type events.

The Nickel Rim South seismic array has the benefit of both hangingwall and footwall access (Figure 5). In 2014 there were a total of 44 sensors with an average sensor spacing of 120m. Some bias towards the west flank of the orebody exists for sensor location as this is where most of the development was in the early days of the mining (2007 to 2009) and development access was conducive towards fast deployment of the seismic array.

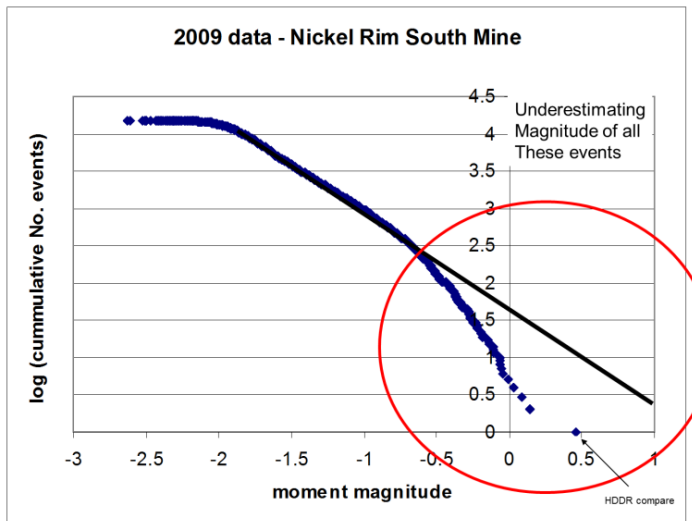


Fig. 3. Seismic data from 2009 collected with uniaxial accelerometers only. The drop off from linearity in the larger magnitude range is due to limited low frequency response of the sensor type. Recorded events above moment magnitude - 0.5 are underestimated in magnitude as a result of sensor type.

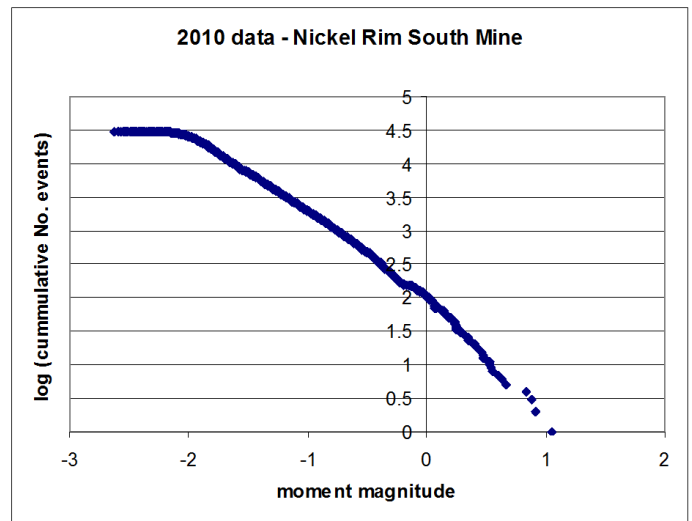


Fig. 4. Seismic data from 2010 collected with a blended array using both 15 Hz geophones and uniaxial accelerometers. Above moment magnitude -0.5, the recorded geophone signals contribute significantly towards the calculated moment magnitude resulting in a more linear relationship to moment magnitude 1.0.

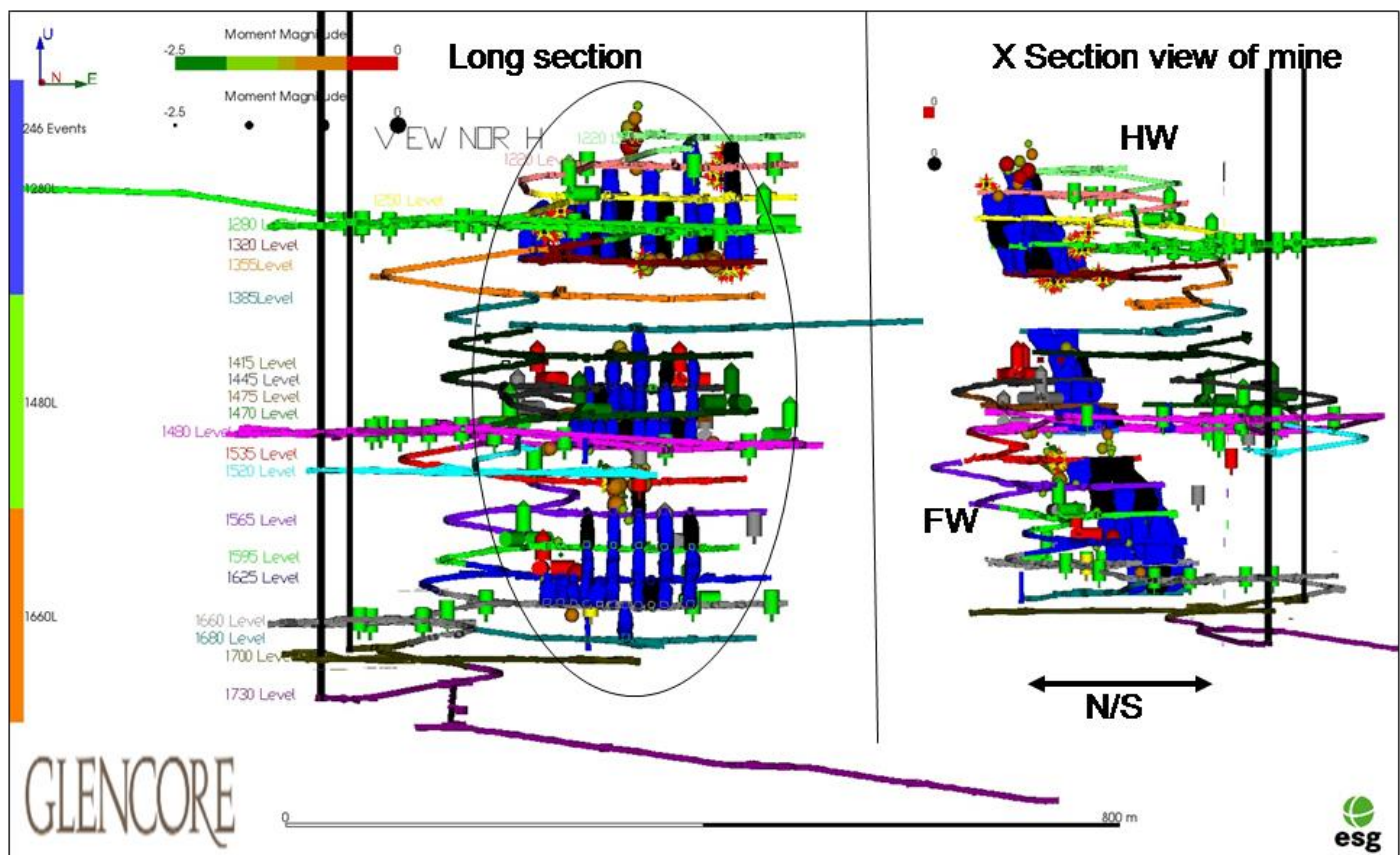


Fig. 5. Nickel Rim South longitudinal and section views of the mine openings and sensor locations are shown. The green cylindrical shapes represent accelerometer locations with red indicating geophones. Level names are in meters below surface. The scale bar is 0 to 800m for reference. Mined out stopes are shown in blue. Typical tunnels are 5x5m in dimension and are indicated in various colours. A total of 44 sensors consisting of 28 uniaxial accelerometers, 2 uniaxial 15 Hz geophones and 14 triaxial 15 Hz geophones monitor a volume of approximately 350m North/South by 375m East/West by 585m vertical. The average sensor spacing is 120m.

The system has been incrementally upgraded since 2009, including the addition of 14 triaxial geophones with average 3D position spacing of 175m. These sensors improve the dynamic range of the system in the lower frequency range, and despite sometimes being in the “near” field of seismic events, give reasonable magnitude estimates to approximately moment magnitude 1.0 (see Figure 4). For magnitudes above 1.0, the moment magnitude is underestimated slightly. 4.5 Hz geophones placed in the far field are used for large event magnitude estimates as well as for correlation to the Sudbury Regional Seismic Network [1].

2.1. Development Blasting as a Source for Seismic Data Analysis

Typical development drives are excavated as a 5.5m high by 5m wide tunnel in 4m advances. Each blast is drilled with a two-boom jumbo and loaded with 250-270 kg of ANFO or emulsion string loading.

The seismic system records continuous data which is then parsed out into triggered seismic event files. A triggered event is recorded in a preset time window, with the actual window depending on the local array. To capture high event rates after blasting and to avoid multiple events per time window, a short 200 millisecond window per event is used for triggering. This short time window works well for the small monitoring volume at Nickel Rim South. The monitoring volume is approximately 350m North/South by 375m East/West by 585m vertical. The short source to sensor distances allows most of the P and S wave energy to arrive within the 200ms. A consequence of the short time window is that a typical development blast that

occurs over several seconds gets recorded as a series of seismic events. Automatic blast flagging is performed by comparing the time between events (rapid succession for blasting) and the magnitude (blasts are always above a minimum threshold). More sophisticated filtering is possible, but manual intervention eliminates the occasional incorrectly flagged blast.

The recorded blasts offer a quick location accuracy check/calibration for the system as seen in Figure 6. The seismic coverage and subsequent results will vary within typical seismic arrays based on sensor location and density. The heart of the Nickel Rim South array generally has location accuracy within ± 5 m of the seismic source. The first shot of the development round can be approximated as a point source as the cut is fired near the centroid of the round. The known location of the blast compared to the system location provides an accurate ± 1 m check on the absolute location error of the system. In other portions of the array, seismic coverage is not as good and location errors can be larger. Figure 7 shows the upper eastern mining which has predominantly hangingwall sensors and sensors below. Location accuracy can be offset as much as 10 to 15m due to raypaths bending around mining, longer sensor to source distances, and a less ideal 3D array.

Another way development blasting can be used as a source of information about the rockmass is to compare recorded source parameter information from the blasts. In theory, each P and S-wave pair represents a development hole being fired. The development blast provides a relatively consistent seismic source.

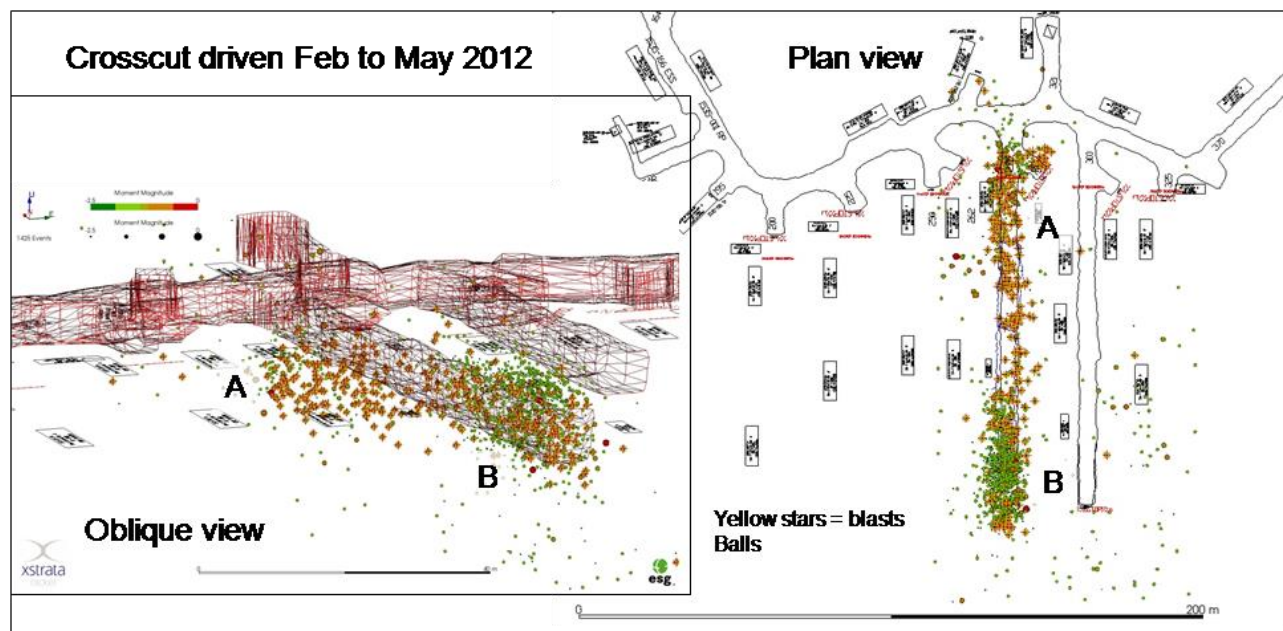


Fig. 6. Nickel Rim South seismicity and development blast “events” around a crosscut access recorded from February to May 2012. In area “A” the plan view tracking of the blasts with the crosscut survey is very good, while the vertical coordinate is offset about 5m. Area “B” has better vertical location control as it is ideally located between the footwall and hangingwall sensors of the seismic array. The yellow/red symbols represent blast events, the green spheres are recorded seismic events.

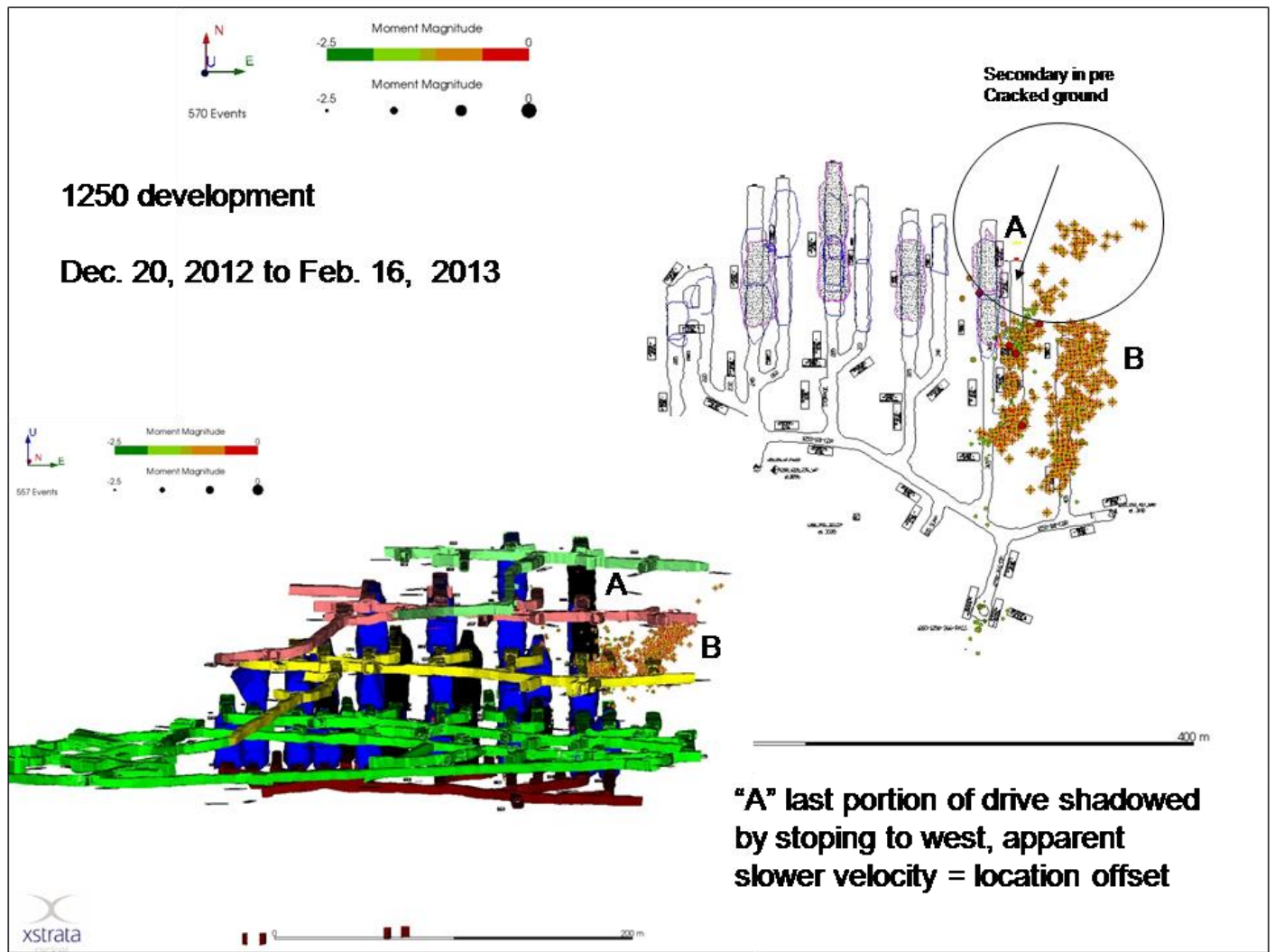


Fig. 7. Nickel Rim South Mine. Two crosscuts (“A” and “B”) in the upper eastern portion of the mine are indicated. The yellow/red stars should track the mine survey if the event location accuracy is 100%. The “smearing” at the end of crosscut “A” is a reflection of slower actual travel time as the raypath travels around the mined out area or through more heavily fractured ground or backfill. A constant velocity model is currently used in the location algorithm and the result is an offset in event location.

Some wave amplification occurs as multiple shots are going off within the blast, and there may be some variation in the recordings due to the state of the rockmass in which the shots are fired, but overall the seismic source is the “same” for each shot. It is believed that significant changes in the source parameter characteristics of development blasts can be attributable to the medium or raypath attenuation effects.

The primary/secondary mining method deliberately creates pillars (secondary stopes) between the primary mining stopes. These pillars yield as they are formed and the seismic records can be used to demonstrate this [2]. A noted feature is the lack of seismic activity when the stope access is driven into a pillar that is in a post yielded state. Development blasts are still routinely recorded and a characteristic high frequency stripping is obvious from the recorded waveforms. Locations of development blast events recorded with high frequency stripping tend to be more poorly located than events

generated from development blast events that contain higher frequencies.

In the ESG system visualization package SeisVis, the best way to visualize the corner frequency deduced from spectral analysis of recorded seismic events is to use the calculated seismic source radius. The corner frequency in the theoretical far-field displacement spectra is inversely related to the source radius of a circular fault plane by the following equation:

$$R = v_s K_{p/s} / 2\pi f_{c_{p/s}} \quad (1)$$

v_s is the shear-wave velocity in km/s, $f_{c_{p/s}}$ is the corner frequency of the P or S waves, respectively, in Hz. K_p and K_s are model related constants. In the ESG system these values are 2.01 and 1.32 after the Madariaga [3] model. It is understood that the circular fault plane model used to estimate the source radius in no way represents the actual mechanism generated from a development blast. The actual values are not truly relevant for the purpose of this analysis. The calculated

source radius is used simply as a means to represent differences in frequency content of seismic recordings. It is the relative differences in calculated source radius values that are important for this analysis.

Figure 8 shows development blasts (shots) recorded at Nickel Rim South over a 15 month period (December 25, 2012 to March 27, 2013). Figure 9 shows a plan view of the development blasts recorded in this period in the stope secondary access area circled in red in Figure 8. Calculated source radius values are scaled in colour from dark green (low) to red (high) and range between approximately 2.5m to 36m during this period.

The seismic source itself (blasting) does not vary considerably between rounds. Each event plotted in Figure 9 represents an individual shot within a development blast. Figure 10 shows the variation of source radius of development blast recordings over time as the development heading advanced. The variation in source radius for each specific blast can be seen by the vertical spread of each specific blast date (calculated source radius range of approximately 2.5m to 36m). The red and green lines represent when the core of the pillar was entered and exited respectively, indicating the time period when the seismic raypaths would be expected to be travelling through more heavily fractured ground. A clear increasing trend in calculated source radius due to decreasing corner frequencies of the blasting records is indicated as the seismic waves generated from the blasts travel through the fractured core of the pillar.

Although each development blast is assumed to be identical, it is possible that shots taken in a more heavily fractured rockmass could result in lower frequency

recordings. Energy could be absorbed within pre-existing fractures and with movement along these fractures during the blasting process. This could contribute somewhat to the higher calculated source radius for development blasts, but each individual blast shot affects a relatively small portion of the rockmass compared to the distance of waveform travel from source to sensor. Also, the blasts located within the fractured ground tend to have a distinct location offset that would not be observed if blasting in more heavily fractured ground was the only contribution to the observed differences from blasts recorded in more solid ground. The geometry of the blast location offsets in secondary developments observed in several areas of the mine indicates that the system velocity used for location is higher than the actual velocity of the medium through which the waves are travelling. The observed location offset coupled with the difference in the recorded source parameter information is interpreted as resulting mostly from raypath effects with the fractured rock in the pillar and surrounding backfill from the primary stopes attenuating higher frequencies from the seismic waves, rather than from variation of the blasting process or the immediate rockmass condition around each shot.

All aspects of the observed differences in the recorded waveforms indicate that development ends for secondary stope mining are being driven in more heavily fractured/failed ground that does not generate much induced seismicity. This is one of the main goals of the planned mining method and sequencing as it significantly reduces risk to underground workers, machinery, and mine production output.

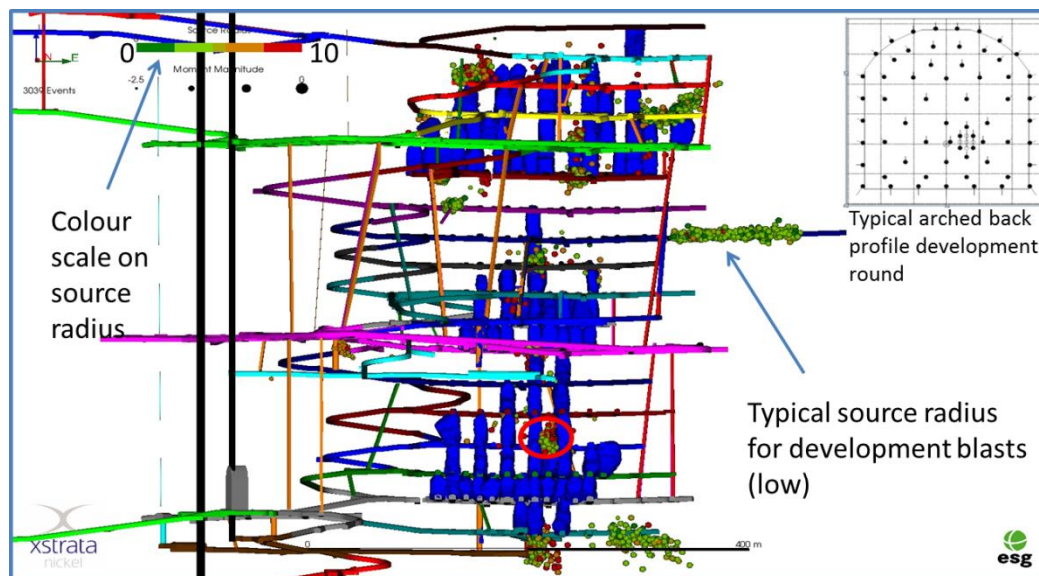


Fig. 8. Nickel Rim South development blasts recorded mine-wide between December 25, 2012 and March 27, 2013. The time frame of plotted seismic events and blast records coincides with the time of driving a secondary stope access through a yielded pillar in the red circled area. The layout of a typical arched back development drill pattern is shown in the upper right corner. The total development round consists of 250-270 kg of ANFO or emulsion string loading. Blast recordings in the ESG system are saved for each shot in the total development round.

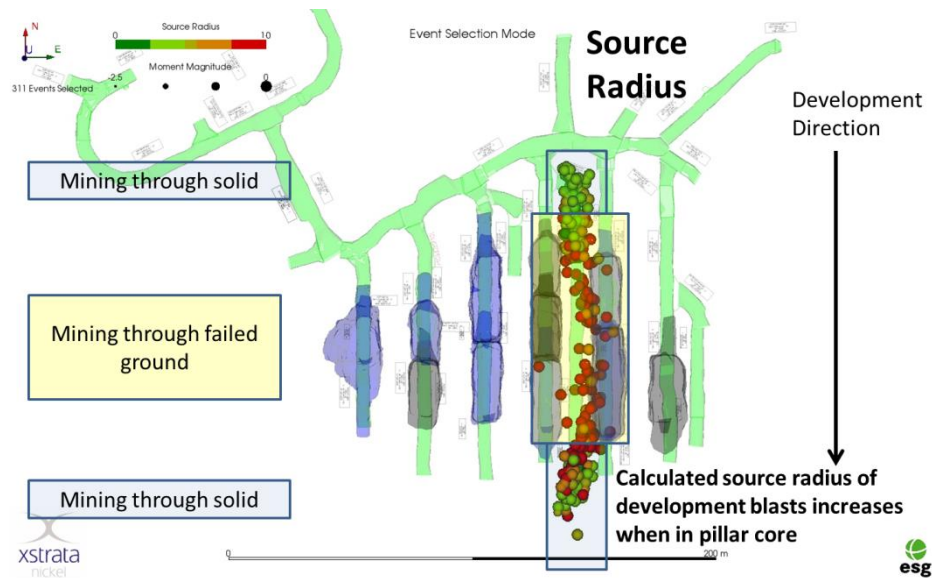


Fig. 9. Nickel Rim South development blasts recorded in a stope secondary access at 1595m below surface. The lower calculated source radius events (green) occur in the footwall and far hangingwall. The larger source radius events (red) locate in the core of the pillar. The loss of high frequency content for waveforms moving through the pillar core is interpreted as indicating that the pillar core was heavily fractured during primary stope mining and the secondary access is being driven through fractured ground.

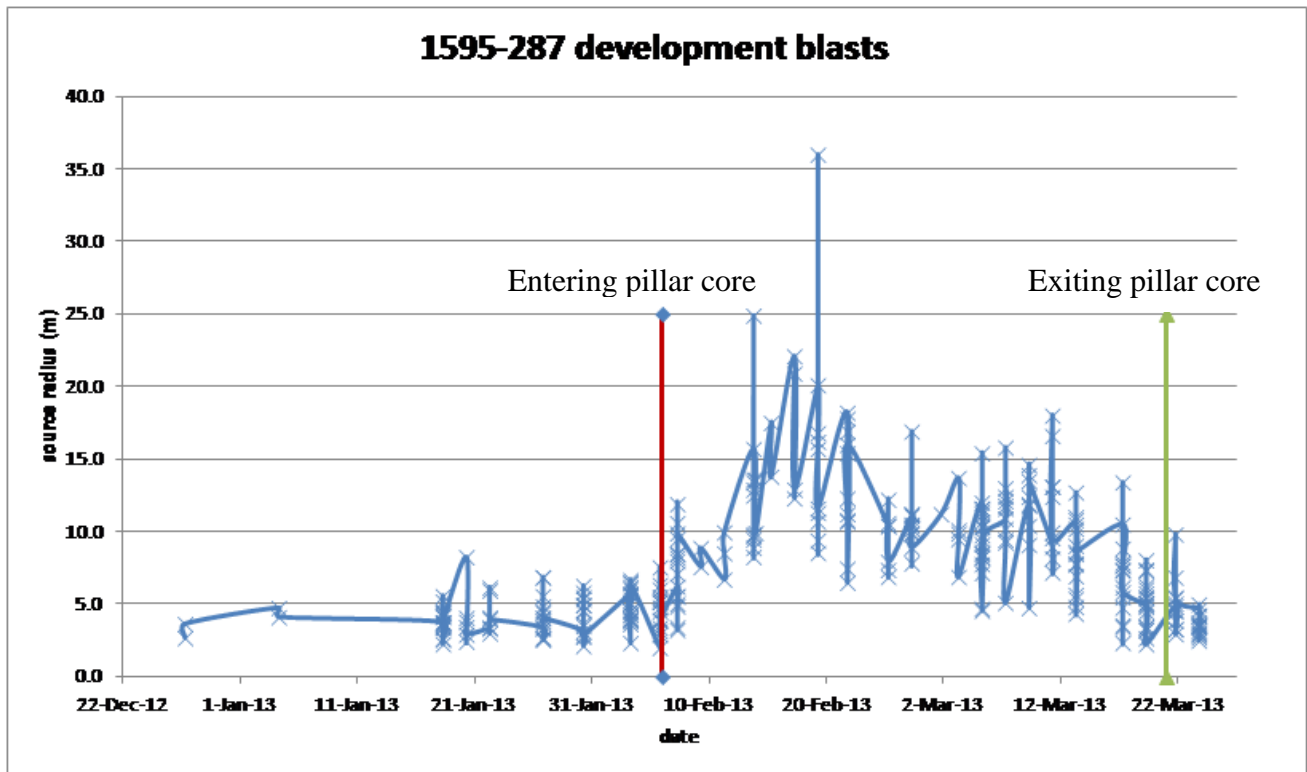


Fig. 10. Nickel Rim South. The calculated source radius for the secondary pillar development blasts is plotted against time from December 22 to Mar 22, 2013. The vertical red line represents when the pillar core was entered by the stope access. Prior to entering the distressed pillar, no high frequency stripping of the waveforms occurs and a low seismic source radius (high corner frequency) from the development blasts is calculated. Within the pillar core, seismic waves generated from the blast are travelling through heavily fractured ground and backfilled areas resulting in attenuation of high frequency signals. The vertical green line on the right represents when the development end went beyond the core of the pillar area. Calculated source radius values return to values comparable to those recorded from blast events from before entering the pillar core, indicating that raypaths are once again travelling through more solid ground.

3. FRASER MORGAN MINE

The Fraser Morgan Mine has a similar mining layout as the Nickel Rim South Mine, but the primary and secondary stopes at Fraser Morgan are 15m wide versus the 12.5m widths in the Nickel Rim South Copper deposits. The seismic array is less precise due to the mining development being less mature and access is only available from one side of the orebody (Figure 11). There is also less overall extraction, so mining induced stresses are currently lower.

The initial secondary access at Fraser Morgan was driven with a less than ideal seismic array (Figure 11 and Figure 12), but the source parameter information from the seismic recordings have proven to be useful even for areas where event location accuracy is less precise (Figures 13 and 14). The development blast data shown in Figure 14 shows a very similar trend to the established case at Nickel Rim South Mine presented previously. The blast data analyses gives corroborative evidence that the mine design is working as intended with secondary accesses being driven “just-in-time” in pre-failed and/or stress shadowed ground after the adjacent primary stopes are mined. The overall lower calculated source radius data from the Fraser Morgan example, compared to Nickel Rim South, may be attributable to the different

seismic array. All sensors are 15 Hz geophones in the Fraser Morgan system and no higher frequency accelerometers are used.

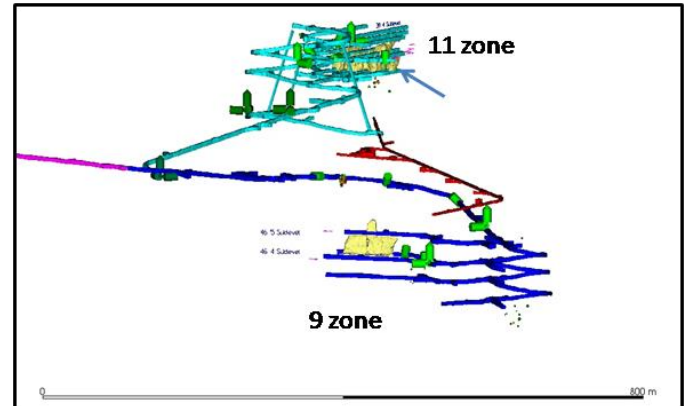


Fig. 11. Fraser Morgan Mine. 3D isometric view of the Fraser Morgan orebodies. In October 2013, 3 uniaxial and 3 triaxial 15 Hz geophones were installed as the first stage of the seismic monitoring program. In December 2014, the number of sensors was increased to 6 triaxial and 9 uniaxial sensors. Array improvements are ongoing.

There is a noticeable difference in the signal to noise quality for the smaller magnitude events recorded at Fraser Morgan compared to the higher frequency accelerometer data at Nickel Rim South.



Fig. 12. Fraser Morgan Mine plan view of seismicity associated with the P6 secondary access development from October, 2014 to January, 2015. More seismicity was recorded in the solid abutment area of the primary stopes compared to the core of the pillar during the driving of the secondary development end as expected. The reduction in seismicity within secondary development is a planned feature of the mining strategy at Glencores' Sudbury Operations that reduces worker exposure to rockburst conditions.



Fig. 13. Fraser Morgan Mine plan view of development blasts recorded in the pillar during the same time frame indicated in Figure 12. Calculated source radius details of each blast are presented in Figure 14 showing higher calculated source radius (lower corner frequency) in the core (red circles) indicating that seismic waves are travelling through a more fractured rock mass.

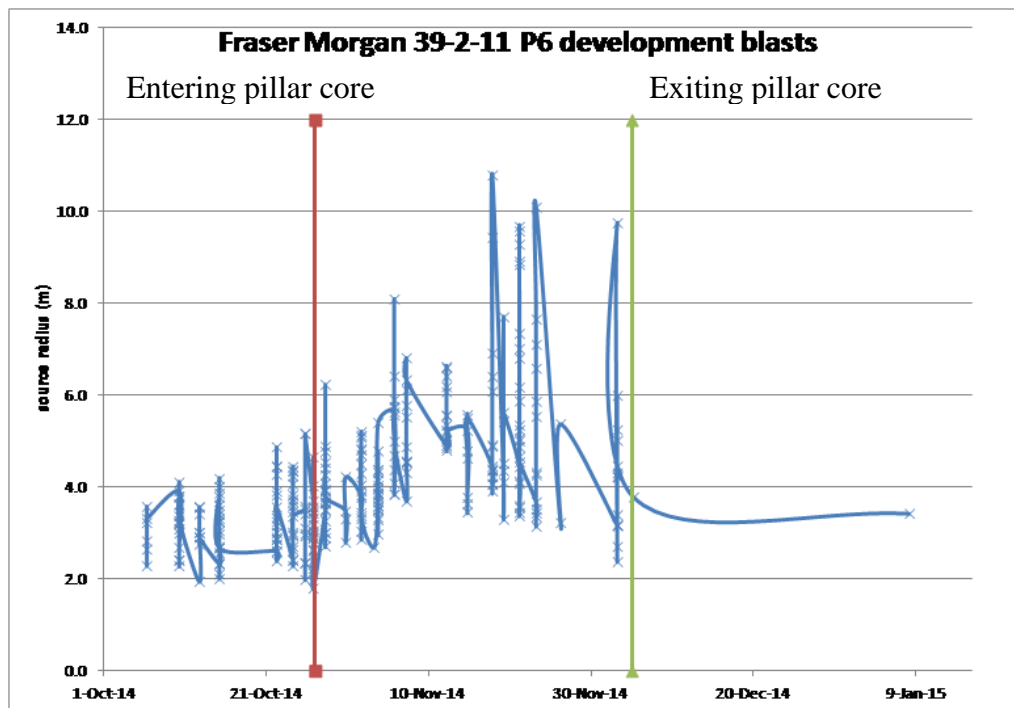


Fig. 14. Fraser Morgan Mine. Calculated source radius of the developments blasts from October 2014 to January 2015 showing a similar trend to that indicated in Figure 10 at Nickel Rim South. A relatively clear delineation of changing rockmass conditions is evident when examining the source radius/corner frequency of development blasts as development proceeds into a rockmass that has been exposed to nearby mining and is expected to be in a distressed condition.

The lack of accelerometer data at Fraser Morgan is most likely responsible for the lower overall calculated source radius values compared to Nickel Rim South. However, the trend of increasing calculated source radius in the core of the pillar is the same. Again, the actual seismic source, development blasts, is assumed to be relatively constant with the variation in source parameters being attributable to changes in the rockmass.

4. FRASER COPPER MINE

The Fraser Copper zone has been mined since the early 1980's, predominantly with narrow vein cut and fill methods. A common issue with this type of mining occurs when two mining fronts converge to form highly stressed sill pillars. In some cases the mining direction is switched from overhand (mining upward with solid rock above head) to underhand (mining below reinforced backfill). This change reduces risk by keeping high stresses below the operating level and the gravity component of potential rock falls is reduced. However, floor heave rockbursting is a risk and face bursting from high stresses ahead of the advancing cut is also a concern.

Figures 15 and 16 show quarterly seismic plots of an underhand mining sequence in the 580 area of Fraser Copper located at a depth of approximately 4600 ft. (1,400 m) below surface. Extensive mining above and below the working area existed forming a highly stressed sill pillar. Mining was stopped due to face bursting issues after two small bursts occurred with each resulting in less than 5 tonnes of rock ejected. Several mitigation methods were in place at the time, including attempts at jumbo destressing and face screening. There were two 3x3m cuts remaining and to further improve safety while extracting this ground, it was decided to trial a long multi-hole destress blast to "push" the high stress further ahead of the man entry area. The observed seismicity was predominantly in front of, and close to, the mining face, with seismicity also observed in the footwall ahead of the face. The seismicity, coupled with underground observation, indicated that the ground for the underlying last cut was becoming fractured. This is the norm for sill pillar mining observed at Fraser Copper. Numerical modelling also predicted yielding of the second cut in these mining conditions.

It was felt that the failed second cut ground on the floor of the area provided a safe area to create a drill cut-out for the longhole pattern. The details of the jumbo destress blast are shown in Figure 17 along with the immediate 24 hour seismic response of the rockmass.

Seismic monitoring in this portion of the mine consisted of uniaxial accelerometers (limited dynamic range up to about -0.5 moment magnitude) in a relatively well covered part of the array. Source location accuracies were in the 5 to 10m range. A characteristic of yielded

ground in deep mining is the change of seismicity for a specific volume of rock over time. Areas that were once seismically active and become "quiet" are typically yielded or stress shadowed. Higher event rates typically relate to higher potential bursting risk. Energy Index (EI) [5] is a relative measure of energy release for a given amount of co-seismic deformation and is calculated from the seismic waveform information. Areas showing higher energy index values generally indicate relative high stress areas or periods.

A brief description of the destress blast example is provided by Collins et al., [4]. A more detailed version is presented in this paper. In the destress blast analysis, the time period corresponding to the highest face bursting risk had the highest average event rate and the highest overall EI (Figure 18). The use of the EI concept to gauge the effectiveness of the destress blast requires high spatial resolution of the seismic system. In hindsight, it is postulated that the blast effectively destressed approximately 10m of the rockmass along the strike length of the vein and two cuts (6m) vertically. The term "destress" refers to a local volume, as the stress is actually redistributed forward into the adjacent solid rock. If too large a volume of rock is selected for the EI analysis, or if the location accuracy is too dispersed, the dataset could contain events unrelated to the destress blast. In this case, the destress area was quite isolated from other mining and it is assumed that all events used in the analysis are related to the destress blast and subsequent rock mass response. Figure 19 shows the EI history of seismic events recorded within the volume thought to be impacted by the longhole blast.

The average EI did show the expected drop in value after post longhole destress blast mining resumed. However, it was not clear immediately after the blast how far ahead the newly stressed region was located. Of concern was at what point mining would reenter a stressed rockmass. After four advances of 2.5m each, the last blast triggered three larger magnitude events ahead of the face of moment magnitude 0.8, 0.8, and 0.9. The overall event rate increased once again, with the events showing an increase in average EI as shown in Figure 20. Underground observations showed that the face area had a visible "dished" shape, indicative of face spalling and high stress. For safety reasons, mining was halted and the entire first cut was filled to allow underhand mining of the final cut which was believed to be in a yielded state. Figure 21 shows the recorded seismicity after mining approximately 80m of the last cut (Nov. 2014 to Feb. 2015). Virtually no seismic activity other than recorded blasts occurred in the plane of the vein, indicating low seismic risk. This seems to confirm the earlier conclusion from the seismic data that the rockmass in the second cut had indeed been destressed by the mining of the highly stressed first cut above.

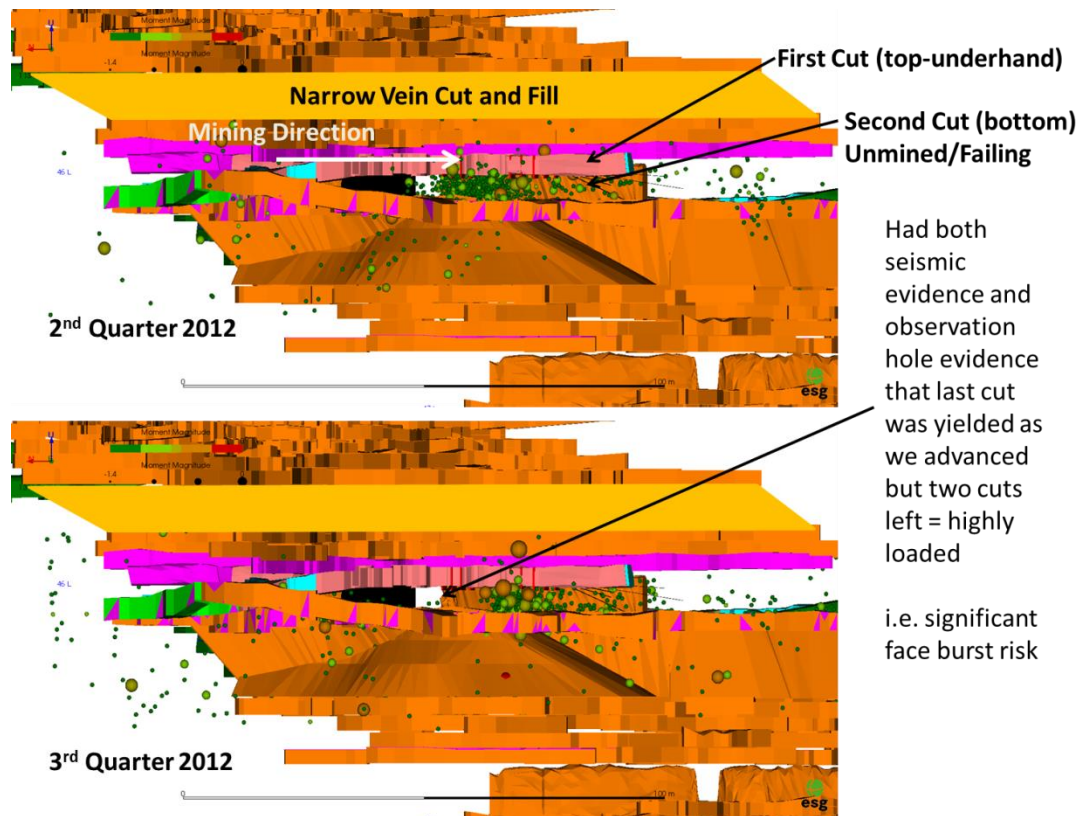


Fig. 15. Fraser Copper Mine long section view from the footwall side of the 6m vertical sill pillar. Quarterly seismic plots of the underhand mining area are shown (Q2 and Q3, 2012). The copper vein was believed to be too flat for conventional blasthole mining. The mining sequence for the first (top) underhand cut is from left to right. Most recorded seismicity locates in the “solid” second cut (below) indicating that this solid ground is fracturing. Second cut yielding is indicated by numerical modelling.

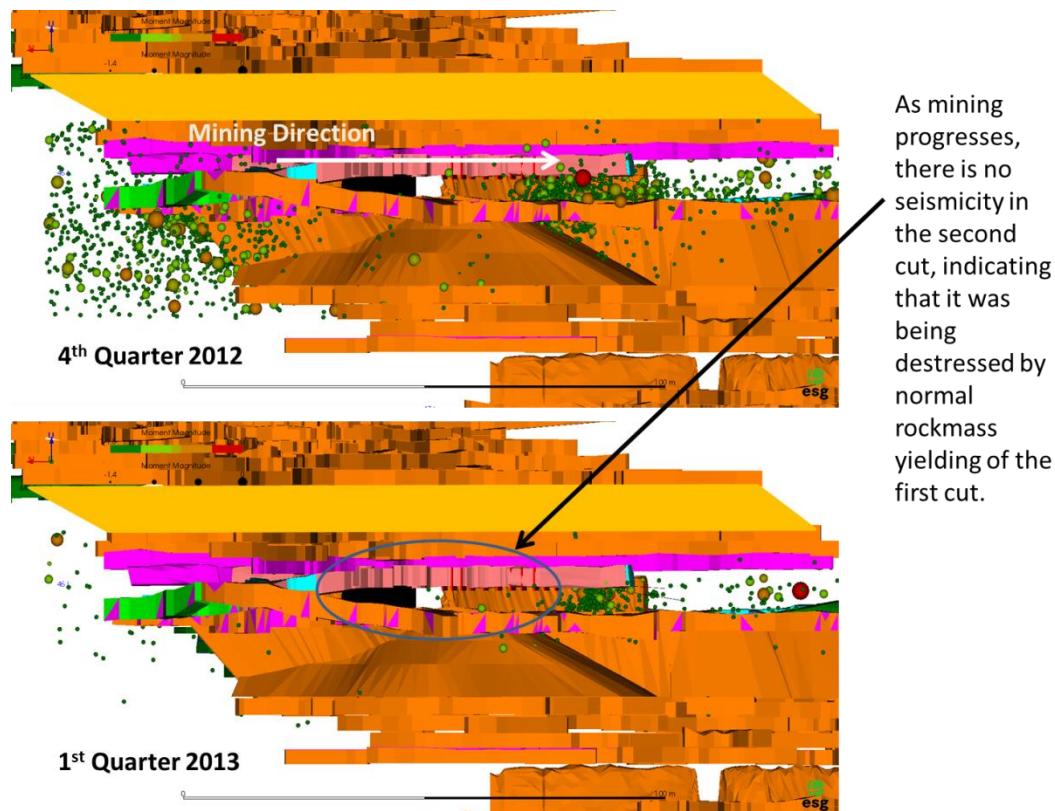


Fig. 16. Fraser Copper Mine 580 first cut mining. Quarterly plots of seismicity for Q4, 2012 and Q1, 2013. The circled area clearly highlights a non-seismic zone that was previously active as indicated in Figure 15. Areas that previously recorded relatively high micro-seismic activity and become “quiet” over time are characteristic of a failed rockmass. Mining sequence is from left to right.

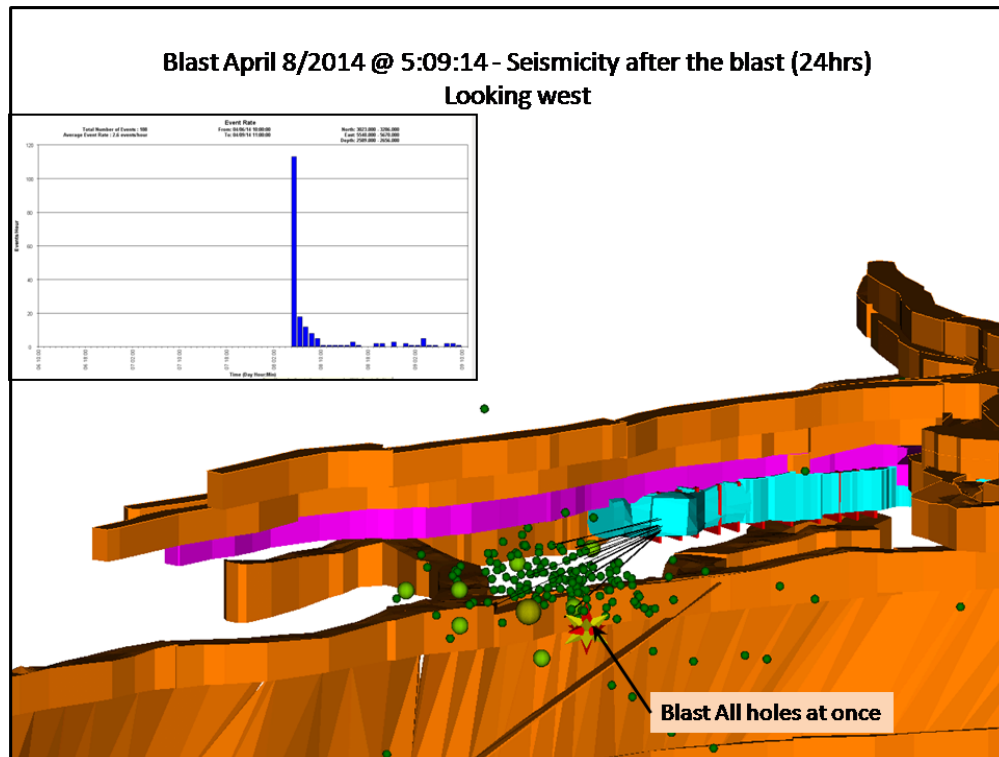


Fig. 17. Fraser Copper Mine 580 destress blast area. Image depicts the same area as Figures 15 and 16 viewed from the hangingwall side. The longhole destress blast pattern and short term 24-hour seismic response of the blast is shown.

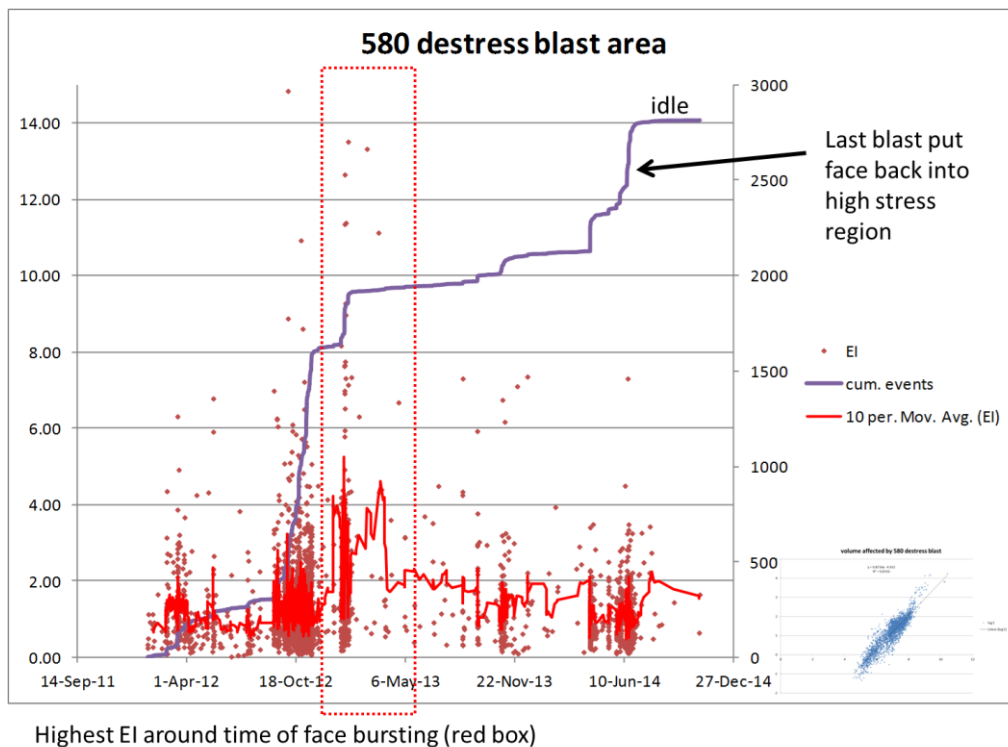


Fig. 18. Average Energy Index (red) and Cumulative Number of Events (blue) are plotted vs. Time for the volume of rock around the 580 destress blast. EI values above 1.0 indicate higher stress than the average for the volume of concern. The Energy-Moment relation for events deemed to be associated with the 580 first cut mining is shown in the bottom right. The high event rate period (dashed red box) corresponded with observed daily rock noise, ground working, and eventually a small face burst at the time of highest overall EI. The flat time periods on the cumulative events plot correspond to mining inactivity. After the April 8 destress blast, the event rate remained low for the next 3 blasts (2.5m advances), increasing after the fourth blast. This is one indication that mining had reached the “end” of the effective destress curtain. Underground observation confirmed that a decision had to be made whether to continue mining in the higher stressed ground, perform another destress blast or stop mining the first cut.

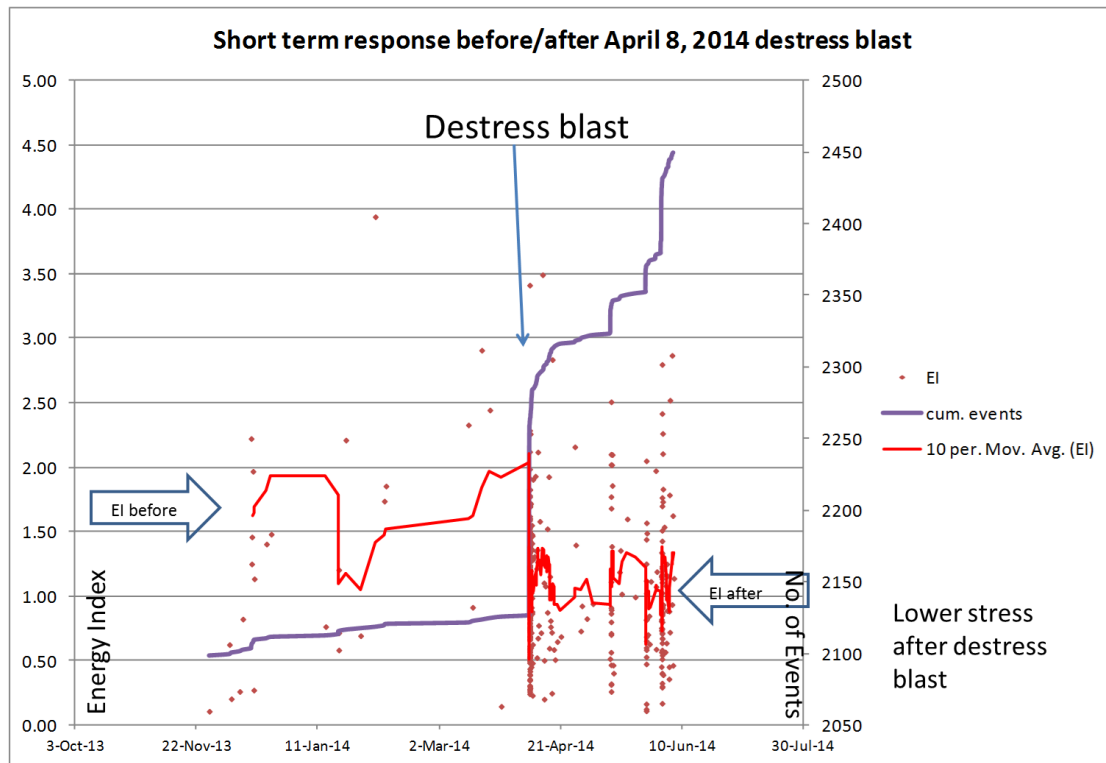


Fig. 19. EI and cumulative number of events just before and after the April 8, 2014 destress blast showing a clear drop in average EI after the blast. Along with underground observations, this analysis provides corroborating evidence that the destress blast was effective in “shedding” stress away from the working face.

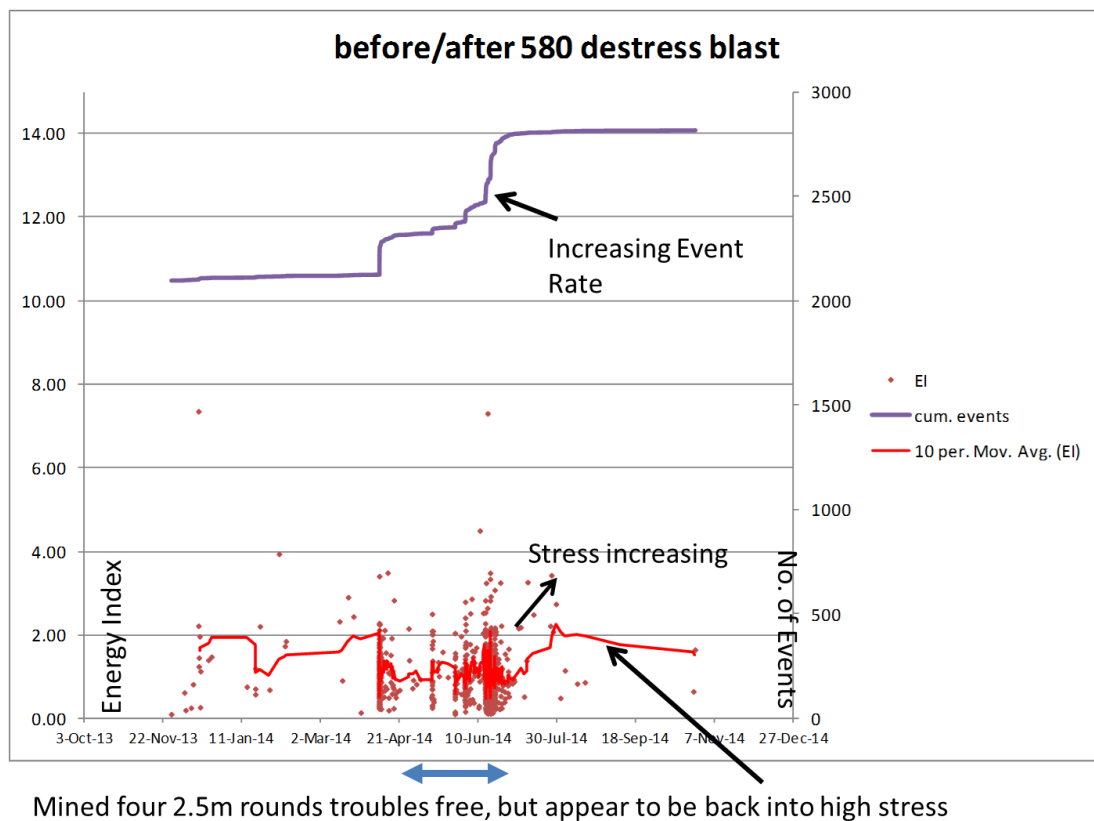


Fig. 20. EI and the cumulative number of events plotted before and after the destress blast showing an increase to pre-destress blast EI levels. This indicates that the mining had advanced to the end of the effective destressed area and face bursting would be at an elevated risk level once again. Mining of the first cut was stopped at this stage and plans were developed to mine the “yielded” underlying second cut.

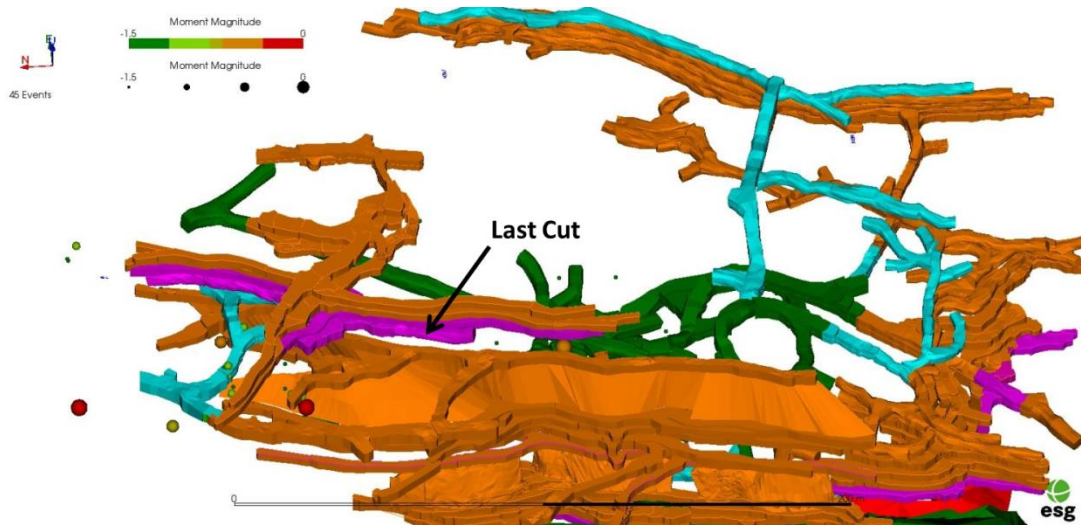


Fig. 21. Mining of the last “yielded” cut from November 2014 to February 2015 had proceeded to approximately 10m from the edge of the longhole destress blast region at the time of writing. Minimal seismicity was recorded in the plane of the vein, with only some sporadic activity in the footwall. The last cut is indicated with mining above hidden from view for clarity.

5. CONCLUSIONS AND DISCUSSION

Waveforms generated from development blasts that are recorded by seismic monitoring systems can provide a rapid assessment/calibration of seismic monitoring array location accuracy. The blast locations should closely track the mine survey if seismic velocities used by the system are accurate. Areas that have significant location offsets (e.g. Figure 7 area “A”) may be due to poor array configuration or convoluted raypath effects. The constant velocity model used for source location algorithms works well for dense seismic arrays where the source to sensor distances are small. However, as mining progresses, the raypaths are progressively impacted by mined out areas. Mining may result in voids that may or may not be backfilled. Waveforms may travel through heavily fractured rock whose rockmass properties (reflected as seismic velocities) may differ considerably from their original condition. Seismic source location accuracy will deteriorate with time unless additional seismic sensors are continually added. CAMIRO Mining Division is coordinating industry funded research with ESG Solutions to create improved 3D velocity models which can be incorporated into real time seismic processing algorithms. An early example of how seismic source locations can be improved with the use of 3D velocity models is presented by Collins et. al., [6] for the New Afton block caving mine in British Columbia, Canada. The CAMIRO project plans to further develop these methods to improve seismic event source location accuracy for mines utilizing their systems.

Seismic records of development blasts can be used to infer existing rockmass conditions. High frequency stripping of the recorded signal occurs as the raypaths traverse fractured ground and/or backfilled areas.

Seismic source parameters such as calculated seismic source radius, which is inversely related to the corner frequency of the seismic events, can be used to show this effect. The development blasts have very similar source characteristics, using the same blasthole patterns with the same amount of explosives. Large variations in the nature of the recorded seismic waveforms are believed to be related to differences in the rockmass or raypath rather than the any differences in seismic source itself. However, this is an area where further study is required.

In the Fraser Morgan example, location accuracy was less than ideal when the seismic array was still in the early stages. However, the development blasts have known locations (mine survey data) and the trends of calculated seismic source radius versus time can be used to infer yielded rockmass conditions (secondary stope development) despite the spatial variance of the recorded seismic data. This provides evidence that planned mining strategies are performing as envisioned and exposure to high stress rockbursting conditions are being managed and minimized for underground workers.

The Nickel Rim South mine array clearly benefits from having both hangingwall and footwall development, offering improved 3D seismic sensor coverage. The mine also had the benefit of very early seismic monitoring coverage. ESG developments for seismic monitoring in the oil and gas sector include the deployment of long strings of sensors in relatively deep holes. The use of this technology for mining provides an opportunity to improve 3D coverage of arrays without having to add, or wait for, expensive mine development for seismic sensor deployment. The first stage in using this technology at Glencore has been implemented successfully at the Nickel Rim South mine. Longhole sensors have been installed in sub-horizontal geological

“scout” holes at over 400m distance to monitor a ramp drive as it passes through a known geological fault. Glencore Sudbury Operations plan to utilize longhole sensor installations, including multi-sensor strings for new mining areas, to get early seismic coverage and improved long term 3D seismic coverage for high spatial resolution of seismicity associated with ramp development and early ore body development tunnels.

High spatial resolution seismic data can clearly contribute to an improved understanding of the rockmass response to mining. In the Fraser Copper destress blast case study, inferences of rockmass conditions in the order of a few tens of meters was important to manage risk in a narrow vein remnant extraction. The Energy Index concept showed the inferred stress state clearly; high EI before the blast, lower EI after the blast, and higher EI again after mining proceeded to the edge of the destressed zone. The seismic data recorded by the ESG system also indicated that the underlying second cut was being destressed due to mining of the first cut. This evidence from the seismic data coincides with numerical modelling results that indicated that the second cut would indeed yield with mining of the overlying first cut. This is an important factor for ground control engineers as it provides some comfort that the models being used for mine design seem to be realistic as borne out by actual rockmass measurements recorded during the mining process.

The use of the types of seismic analyses shown in this paper will only improve our understanding of our rock mass and contribute to improved safe mining and ground control strategies for Glencore. The experience gained during the Fraser Copper 580 destress project will benefit future mining in similar situations and will help ensure the safety of workers. These methods will also reduce the likelihood of loss of equipment or loss of ore reserves that can occur due to rockbursts when mining sill pillars.

REFERENCES

1. Hudyma, M.R. and D.L. Beneteau, (2010), The Sudbury Regional Seismic Network. *CIM Maintenance Engineering and Mine Operations Conference*, Sudbury, Ontario.
2. Simser B. and A. Jalbout. 2014. Rock mechanics tools for mining in high stress ground conditions at Nickel Rim South Mine. In *Proceedings of the Seventh International Conference on Deep and High Stress Mining, Sudbury, 16 – 18 September 2014*, eds. M. Hudyma and Y. Potvin, 189–208. Australian Centre for Geomechanics.
3. Madariaga, R. 1976. Dynamics of an Expanding Circular Fault. In *Bull. Seism. Soc. Am.*, 66, 639-666.
4. Collins D.S., V. Shumila, T. Butler, Z. Hosseini, and C.I. Trifu. 2015. Microseismic Real Time and Advanced Analysis in Mines. In *Proceedings of the 13th International ISRM Congress: Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, PQ*. 8 p.
5. Van Aswegen G. and A.G. Butler. 1993. Applications of quantitative seismology in South African gold mines. In *Proceedings of the 3rd International Symposium on Rockbursts and Seismicity in Mines, Kingston, 16 - 18 August 1993*, ed. R.P. Young, R.P., 261-266. Rotterdam, Balkema.
6. Collins, D.S., I. Pinnock, V. Shumila, C.-I. Trifu, C. Kamp, A. Davies, and A. Chan. 2013. Optimizing microseismic source event location by applying a variable velocity model to a complex geological and mining setting at the New Gold New Afton Block Cave. In *Proceedings of the 23rd World Mining Congress on Advances in Mining Engineering, Montreal, 11-15 August 2013, PDF Paper 674*.