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Assessment of re-entry analysis procedures at an Australian mine

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Abstract

Seismicity caused by mining activity is a significant hazard to the safety of mining personnel and the sustainability of deep underground mines (Potvin, 2009). Following blasting there is an elevation in the level of seismicity as the rock mass responds to a change in mining void (Vallejos and McKinnon, 2008). Areas are typically evacuated during and after blasting, and re-entry analysis is the practice of defining the length of these exclusions of mining personnel based on the time taken for the rate of seismicity to return to a safe level.

Re-entry analysis is simple in concept but difficult in practice. There is no absolute established 'safe level' of seismicity for re-entry as it depends onsite-specific factors. The various measures, such as event counts and cumulative energy plots, used to quantify the level of seismic activity over time are also dependent on the spatial and temporal criteria adopted for blast and seismic data selection.

The objective of this study was to assess the efficacy of the existing re-entry criteria adopted by an underground mine. To achieve this goal, a retrospective study of 2,290 blasts at the mine was carried out. The subsequent recorded seismicity was analysed using a seismic event count method, applying Omori's Law (Utsu, 1961) of seismic decay, in combination with plots of the total seismic energy following each blast. In addition, a 'group event count' method was applied to the data, assessing the seismic response from several blasts without reference to the cumulative seismic energy, in order to average the rock mass response and hence provide a broadly indicative re-entry time for relevant areas of the mine.

It was found that, when analysing several blasts in close proximity to the area of interest to estimate a general re-entry time, more representative results were obtained by expanding the spatial envelope of included blasts beyond the current level-based (i.e. two dimensional) selection used by the mine. Re-entry estimations for all blasts were developed and plotted onto the mine plans, facilitating identification and estimation of the seismic response for future blasts. Through this work, a number of areas throughout the mine were highlighted as requiring more stringent seismic exclusions and/or further analysis, assisting the mine in prioritising risk mitigation measures.

1 Introduction

It is common practice for areas within a mine to be evacuated during and after blasting to reduce exposure to the seismic response as the rock mass adjusts to a change in local stress conditions (Kgarume et al., 2010). The practice of defining the length of these exclusions is referred to as re-entry analysis.

A part of the re-entry estimation requires seismicity to decay to a background level, indicating that the seismic hazard from blasting has reduced to a pre-blast level. An accurate calculation of the background rate is required, with a rate too high resulting in mine personnel re-entering an area that has an elevated seismic risk, while an excessively low estimation of the background rate will result in overly conservative re-entry times and lost production (Vallejos and McKinnon, 2008).

A common industry accepted technique to evaluate the time taken for seismicity to decay to a background rate is Omori analysis (Vallejos and McKinnon, 2008), with Omori parameters used throughout industry assessed in Potvin (2009). Recent literature including Hudyma et al. (2003), Heal et al. (2005) and Potvin (2009) suggests that the energy of seismic events should also be taken into account in order to develop a re-entry estimation that better reflects the seismic exposure to mine personnel.

Seismic exclusion zones are set up, removing all mine personnel from an area surrounding a blast until sufficient seismic decay has occurred, allowing re-entry. The size of these exclusions is based on the coverage of the seismic system, the magnitude of the seismicity that can be expected and experience onsite of the size, type and location of the blast (Vallejos and McKinnon, 2008).

A study was carried out at a seismically active underground mine, with the following objectives:

- To assess the efficacy of the existing re-entry criteria currently adopted by the mine, including both their selection of locations warranting re-entry analysis and analysis methods.
- To compare the re-entry time results produced by different ways of filtering data within the mine seismicity analysis software MS-RAP.

Current site processes in regards to re-entry dictate that only areas with a high expected seismic hazard after blasting are investigated. Through this investigation, re-entry analysis was conducted for a larger sample of blasts, aiming to highlight re-entry times for multiple locations across the site. Key ‘triggers’ responsible for areas of elevated seismic response were also investigated, so predictions could be made about the likely re-entry requirements for future comparable areas of the mine.

2 Mine operations and structural setting

The mine operations presented in this study involved sublevel caving (SLC) of a disseminated orebody. The mineralisation is hosted within much weaker ultramafics with a shear zone along the contact between the hangingwall felsic to ultramafic rock contact. Entry into the orebody has been conducted from the hangingwall side due to the improved strength of the rock mass in the felsics and all crosscuts have to go through the shear zone where they are subject to squeezing ground conditions. Another important geological feature with seismic implications is a felsic intrusion into the disseminated lens, creating a stiffer zone of rock mass within the more deformable ground.

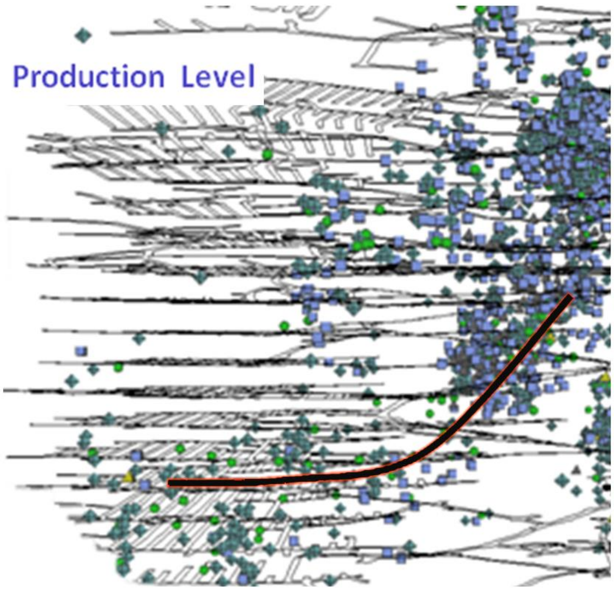


Figure 1 Long section of SLC – seismicity as a result of the high stresses ahead of the cave front

The cave acts as a large mining void due to an inability to transfer stress through the broken rock. The redistribution of stress around the void results in a large increase in stress at, for this case, a distance typically 75 m below the deepest production level. Figure 1 illustrates this issue, with a red line highlighting the 'front' of increased seismicity. Development below the SLC that intersects this seismic front has significant implications for re-entry times and exclusion zones following development blasts.

3 Methodology

3.1 Software and algorithms used

3.1.1 Omori

The Omori Law equation developed in Utsu (1961) is shown in Equation (1). The law was initially developed for use in analysis of the aftershocks rate following large scale earthquakes and has later been implemented in predicting the seismic decay following blasting and large seismic events in mining.

$$n(t) = \frac{K}{(c+t)^p} \tag{1}$$

where:

n(t) = the number of events that are expected to occur per time period after blasting.

K = productivity factor related to the number of events in the sequence.

c = offset time constant.

t = the time measured after the initial event.

p = is a parameter that determines the speed of decay.

An example of the Omori decay is shown in Figure 2. The red dotted line shows Omori's Law with a decay parameter, p = -1.5. Through estimations of the seismic decay parameter, predictions of re-entry times following future blasts can be made by calculating the time taken for seismicity to return to a background rate.

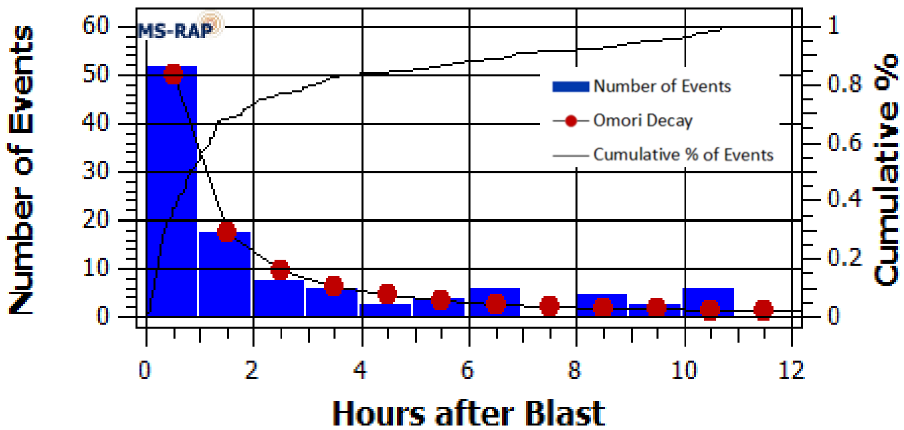


Figure 2 Omori decay compared with the frequency of events following one of the blasts at the mine

3.1.2 MS-RAP

The Mine Seismicity Risk Analysis Program, or MS-RAP software, developed by the Australian Centre for Geomechanics (ACG), has been used throughout this investigation. MS-RAP tracks short-, medium- and long-term seismic hazard variations in time and space and provides a number of seismic analysis tools. MS-RAP version 3 is currently in use in industry and at the studied mine. An updated and soon-to-be-released version 4 of the program was used for the re-entry analyses. The MS-RAP program used to estimate re-entry times for the mine studied assumed the following Omori parameters:

- C = 0.5.
- a productivity factor, k, equal to the number of seismic events within the first hour after blasting.

For this investigation, the Omori decay was used solely as a guide to determine re-entry times. The recorded blast response was analysed to determine re-entry times, reducing any reliance on these arbitrary parameters adopted within MS-RAP. Herein, Omori analysis refers to the use of Omori charts within MS-RAP to estimate re-entry times.

3.2 Measures of seismic activity

Seismic hazard to mine personnel is the likelihood that an event with sufficient energy to cause damage to mine excavations may occur. Hudyma et al. (2003) identifies a lack of knowledge of the distribution of seismic energy following a blast as a key weakness of re-entry analysis using event count methods only. Figure 3 demonstrates the limitation of using event count in isolation. The seismic event rate of occurrence decays such that over 80% of events have occurred after 4 hours, whereas it takes over 10 hours for 80% of the total seismic energy to be released due to a late high energy burst of activity. In this case a re-entry based purely on event count could have exposed personnel to this later seismicity. In such cases where high energy events occur at times seemingly independent of blasting, Omori analysis should not be used to determine re-entry times (Hudyma, 2008). This type of seismic activity is typically associated with slip failures on geological structures, induced by stress changes due to blasting. An understanding of the seismic sources/mechanism is therefore required to ensure that an effective method for estimating re-entry times is used.

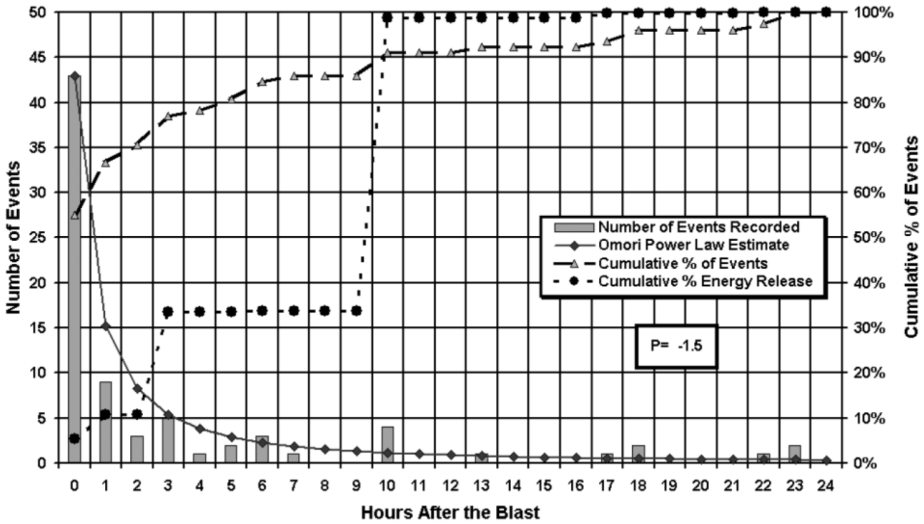


Figure 3 Omori decay with cumulative energy included (Hudyma et al., 2003)

A combined Omori chart aims to capture all seismic hazard to personnel, with re-entry decisions based on the time for seismicity to decay to a background rate, as well as the distribution of energy over time. This method formed the base case for the re-entry analysis on this mine's blast database, against which other re-entry methods were evaluated.

3.3 Blast and seismic data selection

Re-entry analyses were conducted for 2,290 blasts at the mine between April 2009 and July 2010. These comprised production and development blasts.

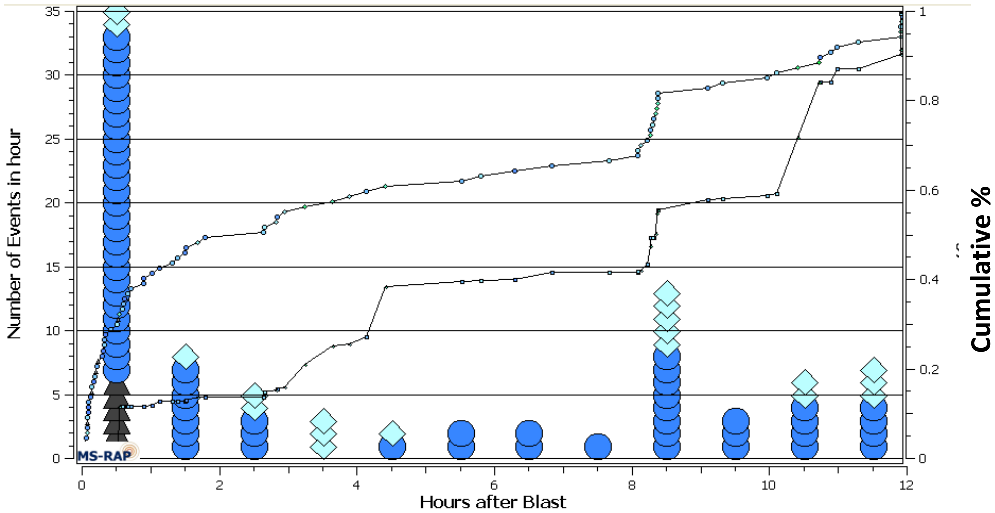
For mine re-entry estimation it is important to define which seismic events are in fact aftershocks to a blast. The density of aftershocks is reduced as distance from the blast increases (Kgarume et al., 2010). Hence a sphere of influence surrounding a blast is developed, such that all seismic events within this zone are likely to be a response to the blast. Current site procedures adopt an arbitrary radius of 50 m for a development blast influence and 100 m for a production blast, comparable to industry distances taken from Vallejos and McKinnon (2008). Since seismicity generated by blasting-induced fresh fracturing is unlikely to occur at such large distances from blasts as 50–100 m, it suggests that geological structures account for much of the seismicity used in these industry determinations (Vallejos and McKinnon, 2008).

3.4 Group event count

Retrospective re-entry analysis is made problematic when the seismic activity recorded after a blast has been limited or sporadic, not reflecting in any way the expected seismic decay. Grouping together blasts from a similar location that share a similar response will result in an event count chart that better illustrates the Omori seismic decay, and thus will be more indicative of the rock mass response for a given location. By stacking a number of blasts into a single Omori chart, a better re-entry time could be determined. Stacking has been used in Kgarume et al. (2010) in order to improve the statistical analysis of event rate decay.

The Omori chart in Figure 4 shows a smooth decay in seismic events until eight hours after the blast. This decay is a reasonable reflection of the seismic decay predicted by the Omori power law, with a sharp rise in initial events, decaying over a short period of time, before becoming relatively stable again. A re-entry decision can be made with more certainty, avoiding the need to make a re-entry decision based on a handful of events.

A limitation of this method results from the effect an individual blast can have on the group result. In the example shown, one blast has a large increase in seismic aftershocks during the ninth hour. None of the other blasts shared this response and yet it has contributed a great deal to the group Omori chart.



Triangles = ML <-2 ; Circles = ML -2 to -1; Diamonds = ML > -1.

Figure 4 Combined Omori chart

The stacking of data from different blasts is only applicable to the Omori decay of event frequency and not for the seismic energy, as the energy released during these events follows a power law distribution. Incorporating cumulative energy criteria into stacked charts results in distributions skewed heavily towards the timing of high energy events, overwhelming the combined contribution of other smaller events. For example, Figure 5 shows that, should a large magnitude seismic event occur in the first hour after blasting, a re-entry time based on when the 90% cumulative energy threshold has been reached would be low, and not representative of the other blast response data.

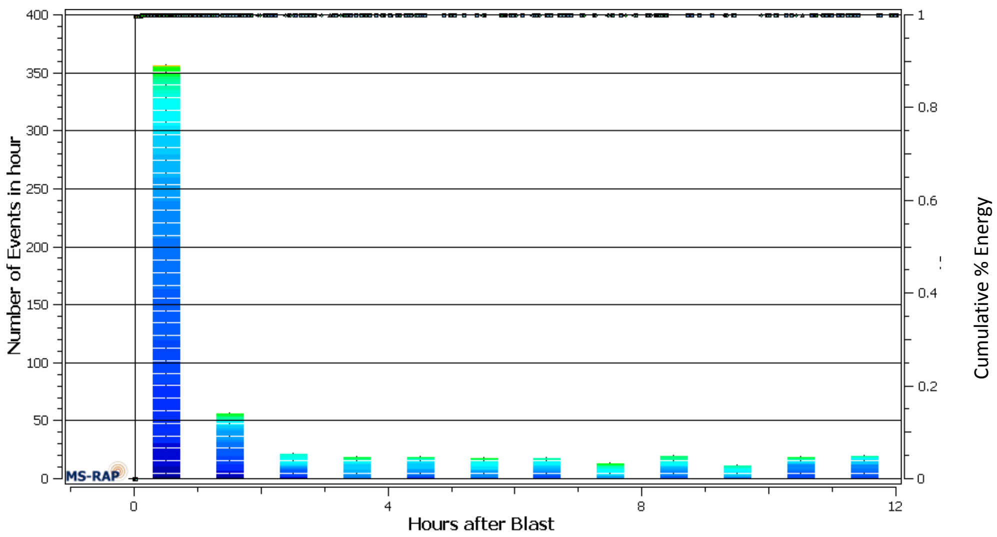


Figure 5 Re-entry estimation using a group Omori approach with energy dictating re-entry time

3.5 Background rate of seismicity

Omori charts have been used to assess re-entry time for a group of blasts, estimating the point in time where the number of events occurring per hour has decayed to a background rate. This study used a proxy background rate, estimated from Figure 6, which quantified the number of events occurring per hour prior to blasting. This method has been used by site personnel, at the studied mine, for real-time re-entry analysis to determine when the seismicity after blasting has stabilised to a background rate. From the figure, the background seismicity can be estimated as approximately seven events per hour, with a rapid seismic decay returning activity to the proxy background rate after three to four hours.

Due to imprecision within the blast database about the exact blast times, the nominal first hour before and 12th hour after blasting show artificial peaks in activity associated with events being wrongly attributed.

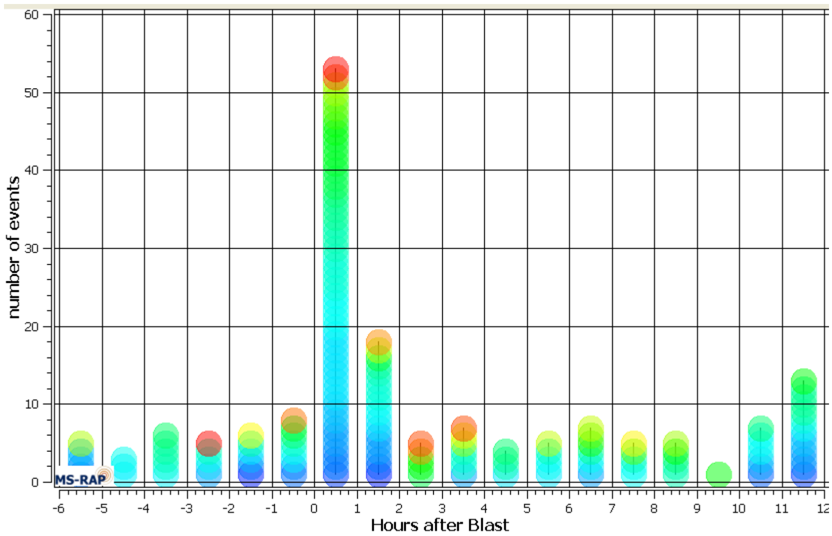


Figure 6 Omori chart, showing all recorded seismic events within 50 m of each blast. Events are ordered by magnitude with low magnitude events at the bottom of each column and the highest magnitudes at the top.

4 Re-entry analysis results

4.1 Blast database

The majority of blasts fell within end-of-shift time windows, namely 06:30–07:00 or 18:30–19:00. Where an exact time of blast was not known, following the site practice an arbitrary blast time of either 06:45 or 18:45 was adopted for the initial Omori analysis. An Omori chart, such as shown in Figure 7, was then plotted and, should it show a spike in events followed by decay, a more exact blast time could then be assumed to be just prior to that 'spike'.

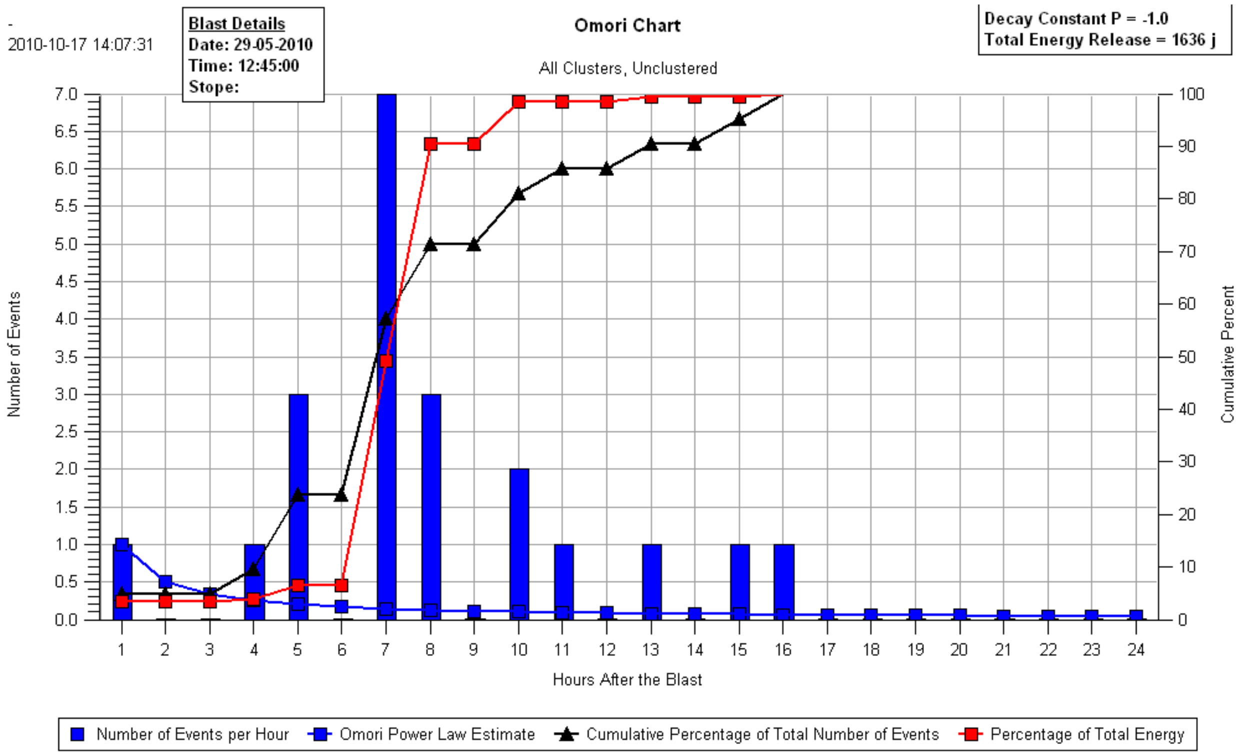


Figure 7 Estimation of blast time using Omori analysis

4.2 Radius of influence of blast

A plot of all seismic events within 12 hours after blasting, organised by coloured markers into percentiles indicating the cumulative number of events that have occurred at a given distance from a blast, after a given time period, is shown in Figure 8. Each shaded band represents 10% of the events. Looking at all events at a certain distance from the blast, at least 60% of them will have occurred earlier, whilst 30% will occur after the 60% to 70% shaded band.

The relative rate at which events are occurring is slowing down as the distance from the blast increases, with large variations between events at each distance interval up until an approximate distance of 100 m from the blast. Beyond about 100 m from the blast, reflects the background seismicity and is highlighted in the chart as vertical boundary lines between the coloured percentile bands. It shows that at great distance from the blast, events occur with the same relative frequency over the 12 hour period, so the events are not blast induced. The steady background distribution of events after 100 m is better delineated later in time when less blast related seismicity would be expected, given the seismic decay.

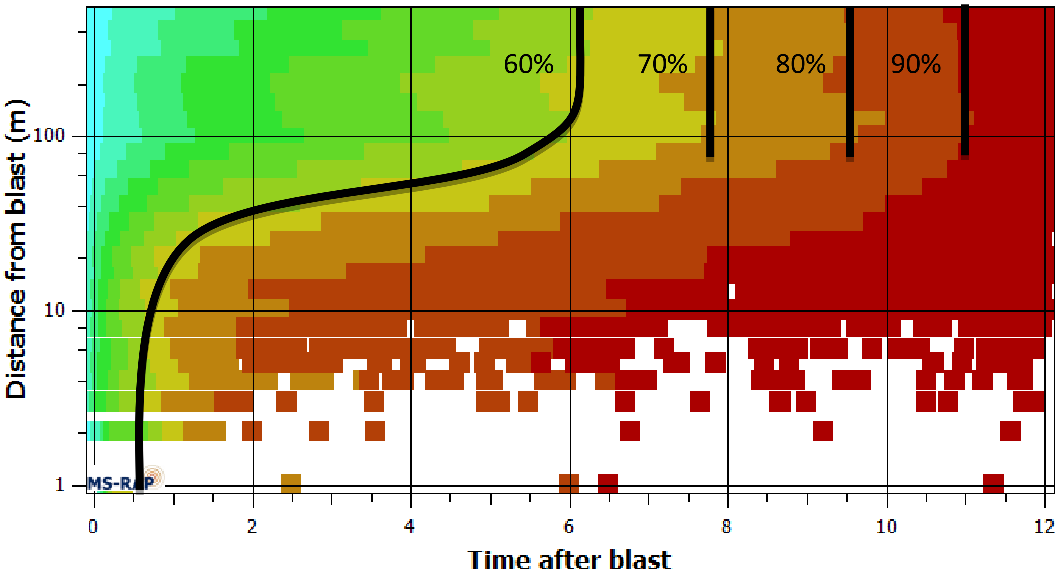


Figure 8 Distance to time after blast (in hours), colour coded to indicate proportion of events at a given distance from the blast exceed a given time

From Figure 8 it seems that blasting has minimal effect at large distances and that 100 m was a reasonable upper limit for the assumed range of influence for production blasts. The analyses therefore provided good evidence not to increase the current assumed range of influence beyond 100 m for production and 50 m for development blasts.

4.3 Background rate of seismicity

The estimations of background seismicity for this study used a grid method of summing the number of events within an arbitrary volume of rock. This limited the ability to assess individual re-entry times based on event counts returning to a background rate of seismicity. The background rate of seismicity investigation instead focussed on identifying areas with greater relative seismic hazard, which have a greater requirement for re-entry estimations. Taking into account the changes in the sensitivity of the current seismic system across different mine locations is a necessary step to achieving accurate assessments of re-entry times based on event counts.

An analysis of the sensitivity of the mine's seismic system was carried out and showed good sensor coverage and adequate system sensitivity for the sublevel cave's disseminated orebody. The setup of the seismic system was evident with all sensors located on the hangingwall side and a general sensitivity threshold M_{min} of -1.5.

A method used to investigate the degree to which seismicity is triggered by blasting can be assessed through the use of a diurnal chart (Hudyma, 2008). The diurnal chart shown in Figure 9 shows an elevated seismic response around firing times whilst the seismicity that is present is relatively constant for all other hours of the day. Important to note is that the number of significant events (with local magnitude greater than 0) are elevated specifically during the end of day shift firing time, when the majority of larger stope blasts occur. Across the mine, seismicity immediately following blasting is approximately two times the background rate, however, when looking at a diurnal chart on a local scale, the difference between seismicity immediately following blasting at other times is much greater. This increase in seismicity following blasting poses an increased seismic hazard to mine personnel, once again highlighting the need for re-entry analysis and the use of seismic exclusion zones.

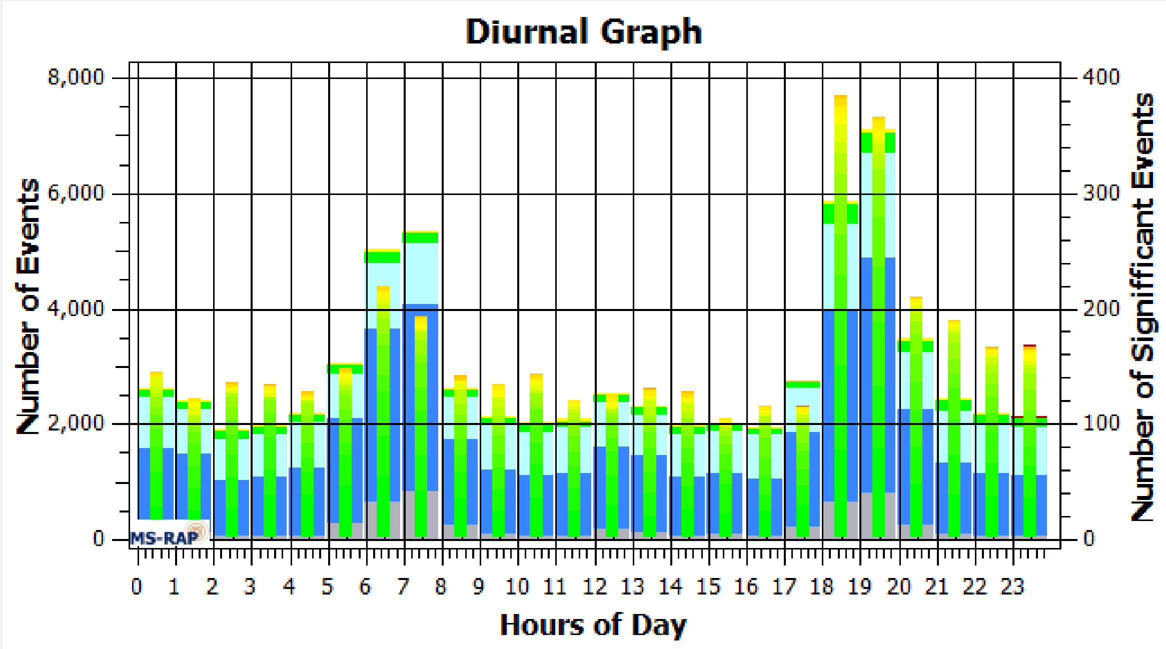


Figure 9 Diurnal chart of all seismicity at the mine from May 2007 to July 2010 with significant seismic events (magnitude > 0) added as narrow bars. Colour coding of bars is based on magnitude ranges from low (darker shading at the bottom) to high (narrow band of dark shading at top)

In the MS-RAP program, nodes are created along planned or surveyed mine drives and are referred to as 'minodes'. Locations throughout the mine can be colour coded using these minodes to compare the background rates of seismicity. In Figure 10, the minodes along current and future development areas within the SLC are plotted as spheres, colour coded to represent seismicity rates relative to the background rate. As the scale suggests, darker shading indicates areas of the mine with a higher rate of seismicity relative to the background rate. For example minodes with the darkest shade represent areas with greater than four times the background rate.

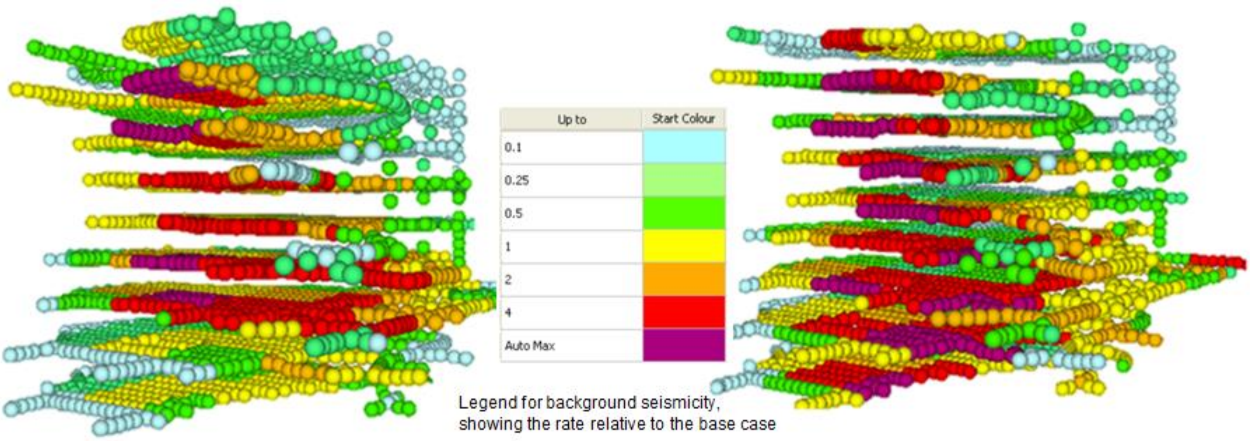


Figure 10 Background seismicity of SLC: May to Dec 2009 (left); Jan to July 2010 (right)

Figure 10 shows the relative increase in seismicity in the SLC area as mining progresses from 2009 to 2010. The SLC has good seismic system coverage which is important for meaningful evaluations of background seismicity. Seismicity generated during 2010 increased significantly at lower depths compared to the background rate of seismicity during 2009. The seismic response adjusted to the change in the mining void over time with deeper development resulting in a shift towards increased seismicity at lower depths.

The lower two levels shown in Figure 10 are minimally developed, showing the current limit of development in the SLC. The increased seismicity below the current development levels illustrates the seismic front ahead of the SLC, indicating that future development will be occurring through highly stressed ground with significant implications for seismic hazard and re-entry evaluations.

4.4 Re-entry analysis criteria at site

Omori charts are used onsite to assess re-entry times following blasting in both retrospective back analysis of blasts and real time analysis. Retrospective analysis was similarly conducted for this study and then an event count method was used to determine re-entry times for blasts occurring in the mine between 14 April 2009 and 23 July 2010.

Retrospective back analysis involves using historical blasts to determine appropriate re-entry times for future blasts. The key re-entry criteria adopted by the mine and used for Figure 11 are:

- Distance range from blast to included event for development blasts = 50 m, production blasts = 100 m.
- Re-entry is permitted at 90% cumulative energy, a value closer to 100% is used when there is a larger seismic response.
- Total energy released following blasting of greater than 100 joules of radiated seismic energy warrants re-entry analysis.

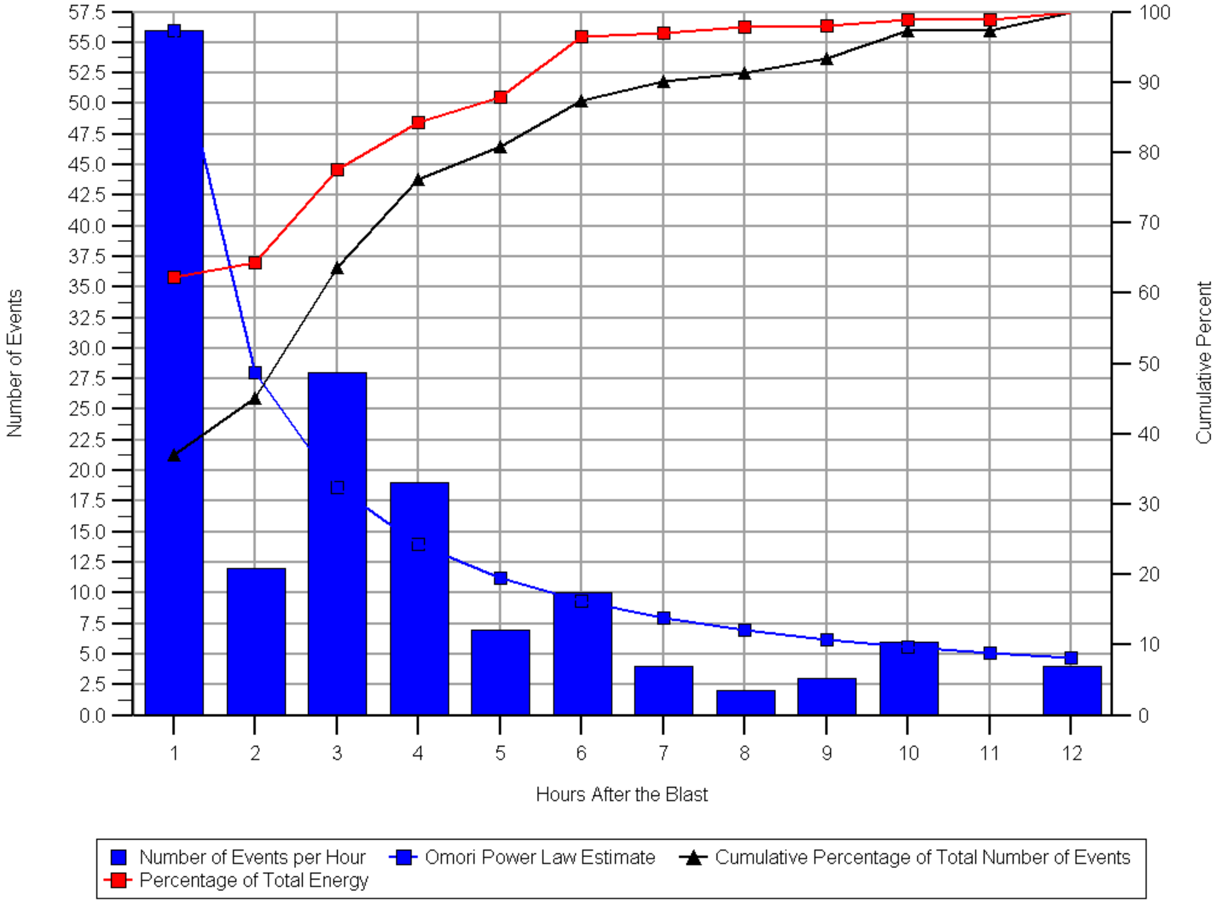


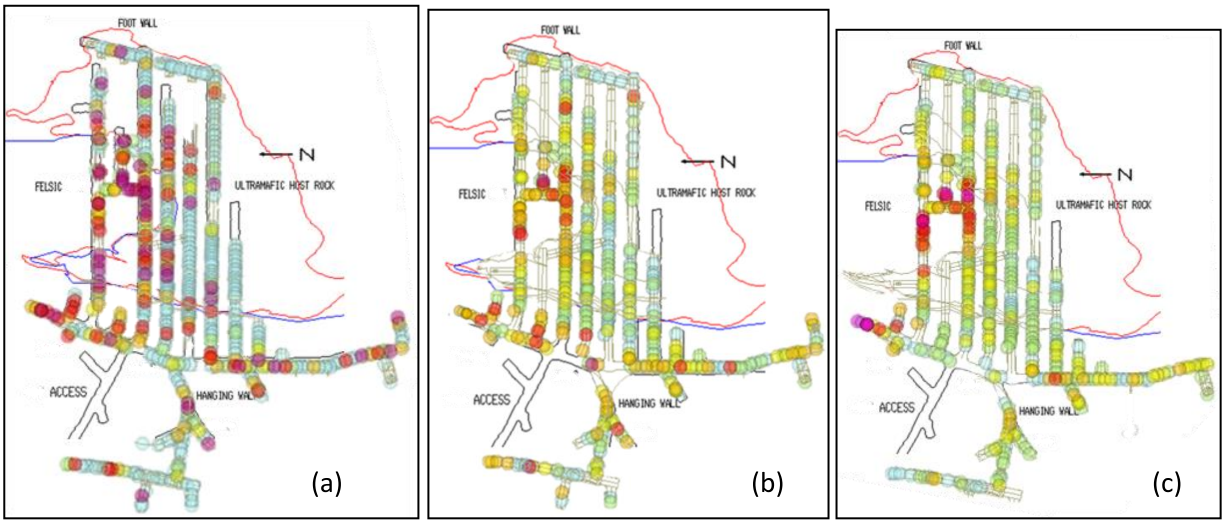
Figure 11 Omori chart depicting seismic response following a blast combined with cumulative energy

The example shown exceeds 100 J, warranting re-entry analysis by the site. The cumulative seismic energy released after the blast reaches the 90% threshold at approximately six hours. Under site methods, this calculated re-entry time, in conjunction with those of other blasts along the same drive, would then be used to develop the length of seismic exclusion times for application to future comparable blasts.

4.5 Individual blasts – event count and seismic energy

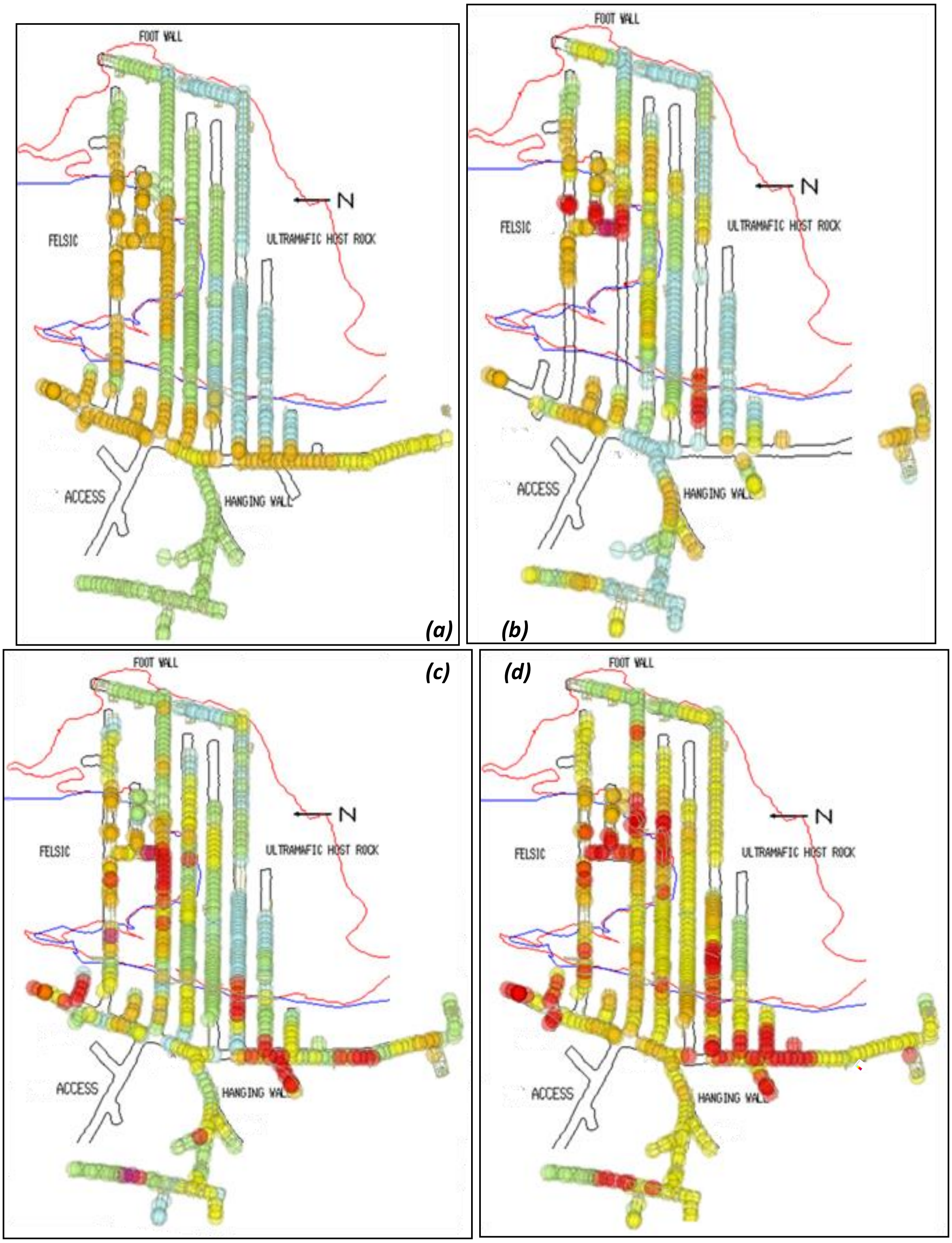
This section discusses comparisons between different ways of estimating re-entry times (namely event counts and seismic energy) while the next section looks at various data grouping approaches in retrospective analyses to estimate appropriate re-entry times for future blasts. To illustrate the different methods, the most complete development level within the disseminated orebody on which a large number of blasts took place during the study period is presented. The near vertical nature of the orebody means that results on one level can often be broadly applicable to future development on lower mine levels.

A plan of level development as of 24th July 2010 is shown as background in Figures 12 and 13. It has a typical SLC level layout with access to the disseminated orebody from the hangingwall side. The hangingwall drive is developed north and south of the access whilst cross cuts through the orebody are developed east to the footwall. Production blasts progress in the opposite direction back West from the footwall towards the hangingwall drive. The grey line surrounding the upper development areas indicates an ore grade boundary and is used to define the orebody. A lithological boundary between a brittle felsic rock mass, where seismic activity is predominantly found, and the softer Ultramafic host rock is also shown. The felsic intrusion into the weaker host rock can be seen, labelled ‘felsic’. The seismic response, specifically time to re-enter after blasting, will be seen to depend on the geology as well as the direction of mining.



Re-entry estimation measured in hours	Total radiated energy in Joules	Cumulative number of events after blasting	
Up to:	Up to:	Up to:	
1	10	2	
2	100	5	
3	1000	10	
6	10,000	20	
9	100,000	40	
Auto Max	Auto Max	Auto Max	

Figure 12 Development blasts on a level: (a) individual re-entry times using MS-RAP Omori analysis with a 90% cumulative energy threshold; (b) cumulative energy mapped to development blasts;
(c) cumulative number of events mapped to development blasts. Legend included for colour coding



Legend for all re-entry estimations measured in hours						
Up to:	1	2	3	6	9	AutoMax

Figure 13 Development level: (a) re-entry times for individual blasts averaged into manually selected areas; (b) average of individual re-entry times using cumulative energy, 10 m radius; (c) re-entry times per blast using group event count, 10 m radius; (d) re-entry times per blast using group event count, 30 m radius

An analysis of re-entry times across the level was conducted, with results shown in Figure 12, plotting the seismic response to individual blasts as colour coded spheres using darker shading for the highest values down to lighter shading for the lowest parameter values. Figure 12(a) shows re-entry times determined from Omori analyses using a 90% cumulative energy threshold. Figure 12(b) plots the total seismic energy of events associated with each blast within a 50 m radius and Figure 12(c) similarly shows the total event count within a 50 m radius.

Conditions in the felsic rock mass are much more conducive to seismicity, as stress builds before being released. The plots clearly show the role of such rock mass properties in defining the areas of the production level that require longer times for re-entry. For example, darker blasts, signifying the highest re-entry times, are largely concentrated within and immediately surrounding the felsic intrusion. Re-entry times rapidly decrease as development moves further into the softer, more deformable host rock.

Seismic energy mapped to blasts shown as lighter shading in the left plot do not exceed the 100 J energy criterion, above which the mine considers the blast to warrant re-entry analysis. The analysis results in these low hazard areas thus support the mine’s general finding that the majority of development and production blasts in the SLC orebody do not require re-entry analysis.

The cumulative number of events following a blast on the level has been plotted as another comparison to re-entry times and energy for the level. Cumulative events are mapped to each blast in Figure 12 (right column) with the same colour convention as before—lighter shading for few events up to darker shading for higher counts. The high event count areas were found to correspond to areas with high background seismicity. As a result background seismicity can possibly be used as another indicator of areas that will require re-entry analysis.

Although a general relation appears to exist, there is still a large variability in the number of events, radiated energy and the re-entry times estimated for individual blasts. An example of this can be seen just north of the SLC access where a group of blasts exhibit a low number of seismic events, a medium to high rate of energy released and medium to high re-entry times. This may be representative of seismicity in a felsic pillar zone, compared to the adjacent development into abutments typified by high energy and event counts in felsic abutments, versus low energy and seismic activity in ultramafic zones. Analysis of these blasts would suggest that key to determining the re-entry time is a combination of event count analysis and the use of an energy distribution which appropriately reflects the mining and geotechnical setting of the local blast area. Table 1 summarises the seismic response to these development blasts within the geotechnical context.

Table 1 Zones of seismic response to blasting

Plan Location	Re-entry Time Based on 90% Cum. Energy Threshold [Figure 12(a)]	Seismic Energy Response [Figure 12(b)]	Seismic Event Count [Figure 12(c)]	Interpretation of Seismic Response
Felsic intrusion	Long decay time	High energy	High count	Stiff, strong intrusion into deformable ground. Behaving like a brittle sill pillar.
Felsic hangingwall – central	Moderate–long decay	Moderate–high energy	Low–moderate count	Localised response in stiff, strong rock mass with likely structural influence such as movement in the shear zone along the contact.
Felsic hangingwall – north abutment	Long decay	Moderate–high energy	High count	Abutment stress in stiff, strong rock mass.
Ultramafic between felsic intrusion and hangingwall	Long decay	Low–moderate energy	Low–moderate count	Load shedding to felsic intrusion and likely structural influence.
Ultramafic – central SLC	Short decay	Low energy	Low count	Squeezing ground.
Ultramafic abutting felsic intrusion – southern contact	Long decay	Low–moderate energy	Low–moderate count	Blasts in soft ground but longer decay suggests structural influence, e.g. along felsic intrusion contact.

4.6 Grouped data – averaging re-entry times and stacked event counts

Different methods of averaging and smoothing the highly variable individual results of Figure 12 so as to provide more workable and still reliable re-entry estimates were trialled, with the results plotted in Figure 13. A number of mining locations across the level (and comparable to other levels) exhibited an elevated re-entry time compared to surrounding areas, as summarised in Table 1 and shown in Figure 12(a). These areas have been visually identified, allowing for blasts to be grouped based on proximity and a likeness of estimated re-entry times, resulting in Figure 13(a). As the development level immediately below that presented shares a similar seismic response to blasting in the same areas, events on this level were included and averaged to form the different groups of blasts shown.

The averaging process resulted in a reduced variability in re-entry times, capping the maximum average re-entry time at approximately 5 hours, compared with the previous highest re-entry time of between 9 and 12 hours. Such a large decrease in re-entry time, disguising higher hazard areas, would not be a desirable outcome for risk mitigation as it may be the result of an averaging process rather than a geotechnical assessment.

Figure 13(b) aims for less variation than from individual re-entry times and to also avoid the excessive averaging provided by visually assigning blasts. Instead the re-entry time for each individual blast has incorporated the re-entry time of surrounding blasts within a radius of 10 m to form an average. Compared to Figure 13(a), there is a closer link between the actual blast response and the averaged response shown using the second method. The overriding areas of high and low seismic response have not been eliminated, allowing a more accurate re-entry estimation to be made.

A problem with both of these methods is that re-entry time based on an arbitrary energy threshold does not distinguish between different seismic source mechanisms. So a high re-entry time could result from either a large seismic response to blasting or a delayed structural influence. A low re-entry time could be from an initial high energy event or from a minor response with rapid seismic decay.

Event frequency was used in isolation from energy to assess the re-entry estimations for blasts grouped into a single Omori chart. Two variations based on distance from the initial blast are presented in Figures 13(c) and (d). Distances of 10 m and 30 m from the initial blast were investigated, with all seismic events attributed to blasts within the specified range of the initial blast stacked with the seismic response to the initial blast. A distance of 10 m was first used to show a more localised response to blasting with relatively few blasts included. A radius of 30 m was then chosen due to a width of 25 m between development drives in an attempt to incorporate some effect of blasts that occur in adjacent drives. Greater distances used to group blasts tended to excessively smooth the re-entry results, reducing their value for predicting re-entry times for future blasts.

For development blasts an event count method used in this manner tends to more accurately reflect the seismic hazard in high response areas. Both the 10 m and the 30 m method showed higher re-entry times for areas such as the felsic intrusion and hangingwall drives than the manually averaged method shown in Figure 13(a). Re-entry times due to event count appear to place an emphasis on blasts with a larger response which may be more reflective of the perceived seismic hazard.

The benefits of a comprehensive blast database and hence ability to group blasts in a three-dimensional space were seen in the improved reliability and applicability of the re-entry analysis compared to the site's two dimensional level-based grouping. The limitations of the various averaging methods demonstrated in Figure 13 are summarised in Table 2.

Table 2 Results of data grouping trials

	Limitations	**Utility**
Visual averaging of areas	Inflated low re-entry times and filtered out high re-entry times. Distorts understanding of how rock mass is behaving (shedding or attracting load, slip on structures, etc.) by merging seismic responses from different but adjacent rock mass structural zones.	Poorer
Averaged re-entry times using 10 m radius	Looses the link to seismic source. Inflated low re-entry times. Based on energy release rate and not level of seismic energy.	Better
Stacked event count, 10 m radius	Group event counts for different locations will depend on the number of blasts contained within the 10 m radius and not just reflect the rock mass response. Will not distinguish areas based on seismic energy, which is more directly linked to damage.	Better
Stacked event count, 30 m radius	Inflated low re-entry times and filtered out high re-entry times. Distorts understanding of how rock mass is behaving (shedding or attracting load, slip on structures, etc.) by merging seismic responses from different but adjacent rock mass structural zones.	Poorer

5 Conclusions

Two main retrospective methods for re-entry have been evaluated, one which looked at individual blasts and cumulative energy over time, and the other based solely on the event rate without any reference to seismic energy. Variations in the averaging for individual blasts and stacking a number of blasts into the event method have also been trialled. The different approaches were compared to the re-entry analysis base case as used onsite, which assesses each blast individually using a cumulative energy threshold of 90%.

The current re-entry criteria are arbitrary, a fact reflected by the re-entry decisions made onsite which at times adjust the criteria to better match the seismic response in a specific area. It was seen that the distance ranges used for grouping blasts should preferably be based on changes in geotechnical and seismic response zones within the rock mass, rather than adopting an arbitrary mine-wide fixed distance.

It was found that if cumulative energy is required in the re-entry estimation, then blasts should be assessed individually and averaged to smooth out the results. Cumulative energy is most useful in prioritising analyses, highlighting blasts with less than 100 J of seismicity generated and assigning a re-entry time of zero. Averaging the re-entry times at each individual blast location, including re-entry estimations from blasts within a 10 m radius, appeared to provide the best results when using cumulative energy to measure the seismic response to blasting. Areas of high and low seismic response found during the assessment of individual blasts were generally retained using this method, while the extreme variations in some locations were minimised.

The stacked event count method has incorporated the seismic response from a number of blasts, improving the seismic decay shown during Omori analysis. Re-entry times were estimated using the time taken for seismicity to decay to a proxy background rate. Incorporating the seismic events from neighbouring blasts within a range of 10 m seemed to show the greatest potential for re-entry estimation at the mine locations studied, avoiding the excessive smoothing of re-entry times evident in greater distance ranges. Areas exhibiting a high seismic response to blasting in the individual analysis were identified with less variability by the 10 m stacked event count method, allowing for an easy estimation of re-entry times in a given area.

Averaging methods based on energy, and grouping methods based on stacked event counts, each have their own uses and limitations. When using a cumulative energy approach, a number of zero hour blasts and one high re-entry time will be averaged, diluting the impact of the large response and raising the re-entry times for the lowest energy blasts. Applying a group event count method to the same scenario will see the spike in events from the single blast with a large response skewing the re-entry time for all other low response blasts in close proximity.

It was recommended that grouping blasts across a greater distance range, such as 30 m, be avoided due to the increased re-entry times estimated in areas of low seismic response, as well as the reduction in the maximum re-entry estimation observed. It was also proposed that re-entry estimations, where practical, be made for all blasts to develop a three-dimensional representation of re-entry times across the mine. This aimed to increase the scale of data used to determine future re-entry times, minimising the need to base re-entry estimation on only a small number of blasts along a single development drive.

The key to stacked event count analysis is the improved ability to determine the seismic response for an area of blasts by avoiding the sporadic nature of seismicity following an individual blast. The statistical relevance of the re-entry estimation using a larger data set will be increased as a result. Re-entry times, as well as identifying areas of high and low seismic response, were found to be similar between the base case using Omori decay distribution with cumulative energy, and the stacked event count method, indicating its potential use. This method could be beneficial for re-entry estimations, specifically through the possible automation within MS-RAP 4. To gain a better understanding of the range of rock mass responses to blasting, the energy distribution should be considered along with the Omori decay of event rate when evaluating re-entry time.

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