Re-entry Protocols for Seismically Active Mines Using Statistical Analysis of Aftershock Sequences

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ABSTRACT: Re-entry protocols are a tactical approach for controlling risk after blasts and large events in seismically active mines. Based on a survey of 18 seismically active mines, mostly in Ontario, current re-entry practices are summarized. Over half of the surveyed mines use event decay rate as their primary re-entry decision making parameter. We study in detail the applicability of the Omori's law as an equation for describing the event decay rate for more than 250 mining-induced aftershock sequences in seven different mining environments. Practical guidelines for the use of the Omori equation as a re-entry criterion are proposed.

1 INTRODUCTION

Immediately following large seismic events in mines, there is a short-term increase in levels of seismicity, which gradually decays to background levels, typically over several hours. During this time of elevated seismic activity the risk of aftershocks with sufficiently high magnitude to cause damage is also high. Restricting access to areas of a mine for sufficient time to allow this decay of aftershock events is the main approach in re-entry strategies. These conditions are relatively common in Ontario mines, and are expected to become more prevalent as mining progresses to greater depth, including a number exceeding 2km.

As part of long term worker safety program, a MASHA sponsored and WSIB funded research project has been on-going at Queen's University during the last three years. The overall goal of the project is to produce reliable practical guidelines for the development of re-entry protocols in seismically active mines for the range of mining conditions found in Ontario. This paper presents some of the findings and results to date. The first part focuses on a review of the outcomes of a survey of current re-entry practices at 18 seismically active mines (Vallejos & McKinnon, 2008). The second part presents an update of the study carried out by Vallejos & McKinnon (2009) on the applicability of the Omori's law as an equation for describing the event decay rate of mining-induced aftershock sequences. A total of 252 aftershock sequences were analysed in seven different mines in Ontario. We illustrate the concepts and the applicability of the proposed guidelines by a practical example.

2 CURRENT RE-ENTRY PRACTICES

Mainly, two types of analysis were found to be used for re-entry purposes: energy/moment and event rate analysis. Both approaches have advantages/disadvantages. The main advantage of energy/moment over event rate analysis is that strength/magnitude of the event is incorporated into the protocol. The disadvantage is that reliable seismic source parameters are required, which may involve additional tasks such as adjusting the first arrivals of seismic waveforms and incorporation of triaxial sensors into the monitoring network. However, based on discussion with mining seismologists and the results of our survey, seismicity rate is clearly the single most important parameter that is monitored for re-entry protocol (more than 60%, compared to 20% that use energy/moment).

We found that the decision to re-enter was commonly based on the requirement for the monitored parameters to return to a previously defined background/normal level of seismicity for a specified time window, which in Figure 1 is two hours. This period of time of sustained background levels is referred to as the background time window. If the monitored parameter exceeds a pre-set threshold during that time window, the re-entry clock is reset and the restriction continues.

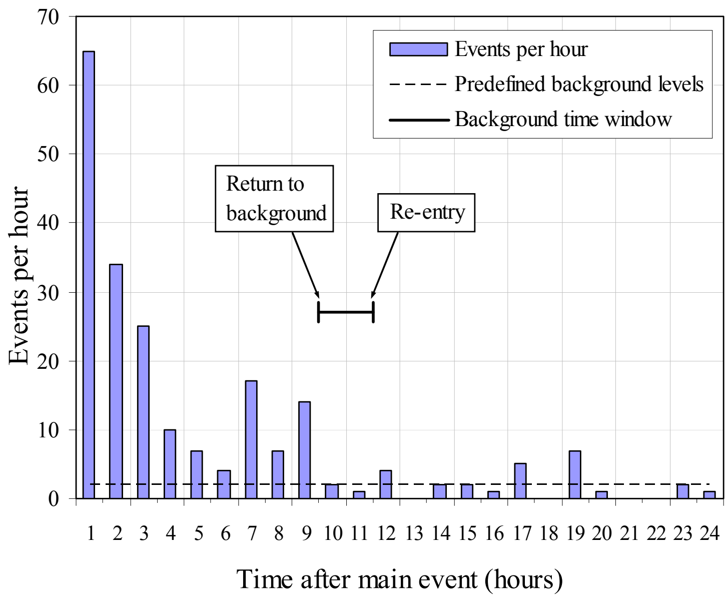

Figure 1. Logic involved in re-entry at the surveyed mines (Vallejos & McKinnon, 2008).

2.1 *Trigger of re-entry incidences*

Ninety percent of re-entry incidents were reported to be triggered by blasting. Since blasting was found to trigger most large seismic events, it would be expected that these events would be relatively close to mining activity. However, it was found that the majority of events triggering re-entry restrictions were located between 50–100 m from mining, which is larger than might be expected on the basis of the influence of stress changes resulting from stope enlargement during blasting. It appears, therefore, that geological structures in the vicinity of mining must account for a significant portion of large events triggered, in addition to fracturing around stopes.

2.2 *tandard re-entry protocols*

A large variety of standard re-entry protocols were in use, many being specific to particular mining activities as shown in Table 1.

Table 1. Standard re-entry protocols at the surveyed mines.

Situation	Re-entry protocol
Development through dyke	2 hours of zero seismic activity
Crown blasts	12 hour background time window
Mining around identified sensitive zones	12 to 24 hours

Sensitive zones may include, amongst others:

- certain geologic structures (faults, shear, dykes and contact zones),
- highly stressed zones (pillars or remnants),
- zones with significant contrast in rock mass properties, and
- local brittle rock mass failure.

Considering this large variation, it is clear that most re-entry decisions are made on a case-by-case basis and that seismicity, and therefore re-entry protocols, are quite site specific.

2.3 *Exclusion zone*

The exclusion zone is that volume around the blast/seismic event for which access is restricted by the re-entry protocol. We found that the most common procedure at the surveyed mines was to restrict access for a fixed distance in all directions from the initial event. For open stope and entry mining methods, distances between 50 and 100m and less than 50m were frequently used, respectively. Exclusion zones larger than 100m were associated with regional fault slip in certain mines.

3 MODIFIED OMORI'S LAW

The high number of mines in Ontario using seismicity rate for re-entry purposes motivated Vallejos & McKinnon (2009) to investigate in depth the applicability of the modified Omori's law (Omori, 1894; Utsu, 1961) as an equation for describing the event decay rate of mining-induced aftershock sequences. The modified Omori's law (MOL), developed from observed decay rates of earthquake aftershocks, states that:

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

where $n(t)$ is the event rate since time t measured from the principal event, c is a time offset constant, p controls the speed of decay and seems to differ from sequence to sequence, with a typical range for earthquakes of 0.6-1.6 (Utsu et al. 1995), and K is an activity parameter that depends on the total number of events within the sequence.

The methodology employed for processing the data and estimating the MOL parameters will be briefly reviewed in the next section; details can be found in Vallejos & McKinnon (2009).

4 METHODOLOGY

4.1 *Identification of aftershock sequences*

For a given zone the start times of aftershock sequences were identified by a modified ratios method proposed by Frohlich and Davis (1985).

4.2 *Filtering*

Each of the identified aftershock sequences were filtered by limiting the source location error-number of triggered sensors (Vallejos & McKinnon, 2008), and by a lowest limit of magnitude, selected at the moment magnitude bin with the highest frequency of events in a non-cumulative frequency-magnitude distribution (Wiemer & Wyss, 2000; Woessner & Wiemer, 2005). These two filters removed poorly located seismic events from the analysis and provided some degree of uniformity in the data, respectively.

4.3 *Estimating the MOL parameters*

The parameters of the MOL are estimated using the method of maximum likelihood (Ogata, 1983). Consider N aftershocks with occurrence times t_i (i=1,.., N) within a time interval [T_A, T_B], where t=0 corresponds to the time of the principal event. An estimate of the parameters K, c and p is obtained by maximizing the following log-likelihood function:

$$\ln L(K,c,p,T_A,T_B) = N\ln K - p\sum_{i=1}^{N}\ln(t_i + c) - KA(c,p,T_A,T_B) \tag{2}$$

where:

$$A(c,p,T_A,T_B) = \begin{cases} \ln(T_B + c) - \ln(T_A + c) & \text{for } p = 1 \\ \left[(T_B + c)^{1-p} - (T_A + c)^{1-p}\right]\big/(1-p) & \text{for } p \neq 1 \end{cases} \tag{3}$$

To evaluate if the MOL fitted parameters adequately describe the aftershock time sequence we make use of the nonparametric Anderson-Darling statistic W^2 (Anderson and Darling, 1954) defined by:

$$W^2 = -N + \sum_{i=1}^{N}(2i-1)\left[\ln(u_i) + \ln(1 - u_{N+1-i})\right] \tag{4}$$

where u_i is the cumulative density function (cdf) after time t_i. For a sequence of aftershocks obeying a MOL process (Equation (1)), the cdf is given by:

$$u_i = \begin{cases} \dfrac{\ln(t_i + c) - \ln(T_A + c)}{\ln(T_B + c) - \ln(T_A + c)} & p = 1 \\ \dfrac{(t_i + c)^{1-p} - (T_A + c)^{1-p}}{(T_B + c)^{1-p} - (T_A + c)^{1-p}} & p \neq 1 \end{cases} \tag{5}$$

A perfect fit to the data is obtained when W^2=0. In this paper we will assume that sequences with W^2≤1.0 fit the data well (Nyffenegger & Frohlich, 1998; Nyffenegger & Frohlich, 2000).

From the above equations, it can be noticed that the estimated MOL parameters depend explicitly on the time interval [T_A, T_B] used to fit the equation. The study of Vallejos & McKinnon (2009) showed that the maximum likelihood estimates of the MOL parameters can be extremely sensitive to this time interval. They concluded and recommended, that for estimating consistent decay parameters, it is necessary to consider only the time interval that satisfies power-law behaviour, i.e., the time interval that follows a power-law (W^2≤1.0) and satisfies c=0. They proposed a uniform method to estimate this power-law time interval. We make use of this method to estimate the MOL parameters for all the aftershock sequences identified. Figure 2 presents an example of the MOL parameters determined using the complete and power-law time intervals. A few remarks can be made about Figure 2:

- Complete time interval:
    1) The estimated MOL curve does not adequately describe the events occurring at very short times (<0.3 hours).
    2) There is high uncertainty in the estimated parameters.
    3) The estimated parameters *K* and *c* appear to be somehow high; however the *p* value is within the range reported in the crustal literature.

- Determined power-law time interval:
    1) Events occurring at very short (< ~0.3 hours) and long (> ~10 hours) times have been automatically excluded.
    2) The uncertainties of the MOL parameters have been considerably reduced and seem more realistic (especially *K*).
    3) We have reduced the number of parameters to specify simplifying the analysis.

This method not only allows us to estimate the power-law MOL parameters but also to have an estimate of the time at which the sequence actually starts the decay process T_S, which in the example presented in Fig. 2 is approximately 0.3 hours.

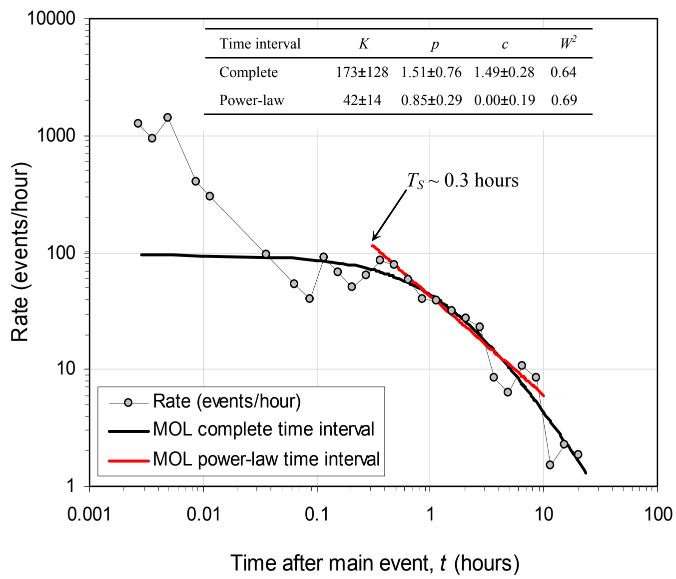

Figure 2. Determined MOL parameters using the complete and power-law time intervals.

5 DATA

A total of 163 mining-induced aftershock sequences were analyzed by Vallejos & McKinnon (2009) from the following four mining operations in Ontario, Canada:

- Copper Cliff North, Sudbury.
- Craig, Sudbury.
- Kidd Creek, Timmins.
- Macassa, Kirkland Lake.

In this paper, for the Copper Cliff North mine, we considered the complete 100/900 orebodies and a different time period, from September 2004 to September 2005.

In order to incorporate a wider range of mining conditions that can be found in Ontario mines, we investigate aftershock sequences for three additional mine sites: Mine A, Coleman-McCreedy East and Williams mine. A brief description is provided for the last two sites:

- Coleman-McCreedy East, Sudbury.
  4400 Level of the 153 Ore body, from January to December 2003. It consists of a complex system of copper-nickel veins that are contained within an east-west striking, southerly dipping breccia zone. Cut and fill production headings with hydraulic fill are used to extract the ore. The microseismic monitoring system covering this zone is composed of 24 uniaxial and 4 triaxial accelerometers.
- Williams Mine, Marathon.
  B Zone 9190 to 9215 – 46 stope, from October 2007 to February 2008. The mining method was longhole open stoping with cemented paste filling. The area mined was a diminishing pillar (2 stope configuration). The microseismic monitoring system consisted of 12 uniaxial sensors. The geology consists of feldspathic ore host, with banded sediments to the north. The ore body dips at 70 degrees and strikes east- west.

An additional 89 mining-induced aftershocks sequences were extracted from the catalogues of these sites. Table 2 presents the number of aftershock sequences identified at each site with their corresponding average lowest limit of moment magnitude M_Z. All sites presented a uniform response in terms of M_Z (small standard deviations) reflecting a consistent sensitivity of the microseismic monitoring systems for locating events above this magnitude for the period under study.

Table 2. Total number of sequences identified at each site with their corresponding average lowest limit of moment magnitude M_Z.

Site	N° sequences	M_Z
A	28	-2.06±0.07
Copper Cliff North	51	-1.64±0.13
Craig	5	-1.71±0.11
Kidd Creek	70	-1.93±0.12
Macassa	51	-1.25±0.08
McCreedy East	24	-2.11±0.11
Williams	23	-1.88±0.13

6 RESULTS

6.1 *Start time of decay T_S*

Figure 3 presents the population distribution of start times of power-law decay for all the sequences analyzed. It is seen that in 98% of all the sequences, decay starts within one hour after the principal event, indicating that for mining-induced seismicity, aftershock sequences display non-power law behaviour only for short times (< 1 hour).

6.2 *Decay p values*

Figure 4 presents the distributions of estimated *p* values at each site. With the exception of McCreedy East and Williams mines, the hypothesis that *p* is normally distributed cannot by rejected at a 20% significance level using the Anderson-Darling normality test. These two exceptions, presented some sequences with high *p* values compared with the rest of their population. A lognormal or inverse Gaussian distribution seems more appropriated for these two data sets. We found that in 98% of the cases, the decay *p* values range from 0.4 to 1.6, with average values between 0.74 to 1.05 (see Fig. 4). Each distribution seems to represent site specific conditions, with higher mean decay values for the Kidd Creek and Macassa sites. In the crustal scale literature, this variability has been related to the properties of the fault system and surrounding lithosphere (e.g., Mogi, 1967; Kisslinger, 1996), but it is still not possible to draw definite conclusions about the significant factors that affects the *p* value in aftershock sequences.

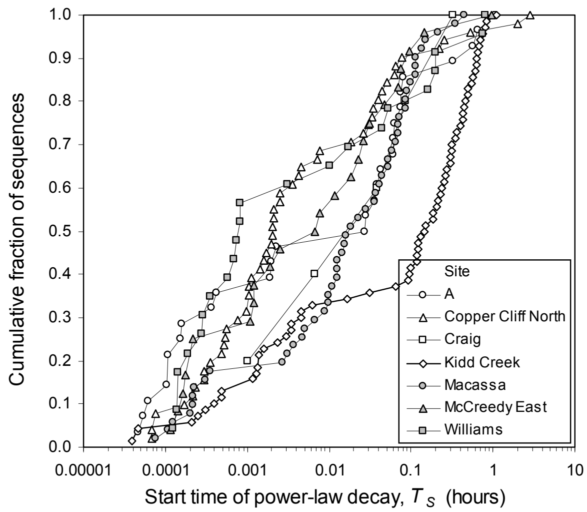

Figure 3. Distributions of start time of power-law decay for the sites analyzed.

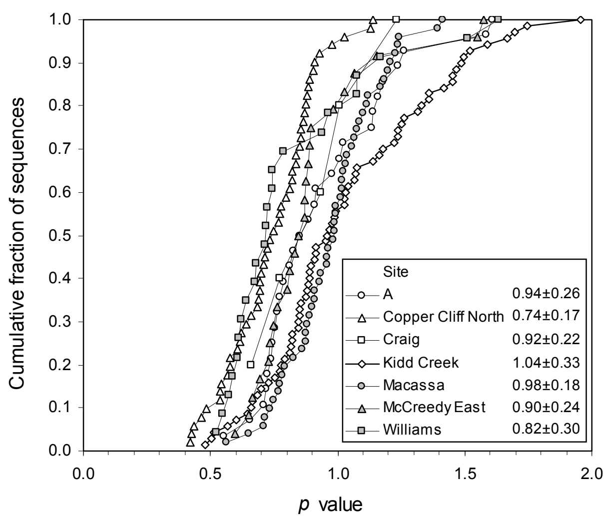

Figure 4. Distributions of estimated decay *p* values for the sites analyzed.

6.3 *K values*

If the MOL equation is adopted with c=0, then K is exactly the event rate at unit time (t=1) after the principal event. However, any estimation of the rate depends on the widths of the bins used to represent the data. This disadvantage lead Vallejos & McKinnon (2009) to attempt correlating the parameter K with the number of events measured during the first hour after the principal event $N_{1\ hour}$. Their analysis showed that K can be satisfactorily expressed by:

$$K = \kappa N_{1hour} \tag{6}$$

where κ is a site specific activity parameter as shown in Figure 5 for the Macassa site.

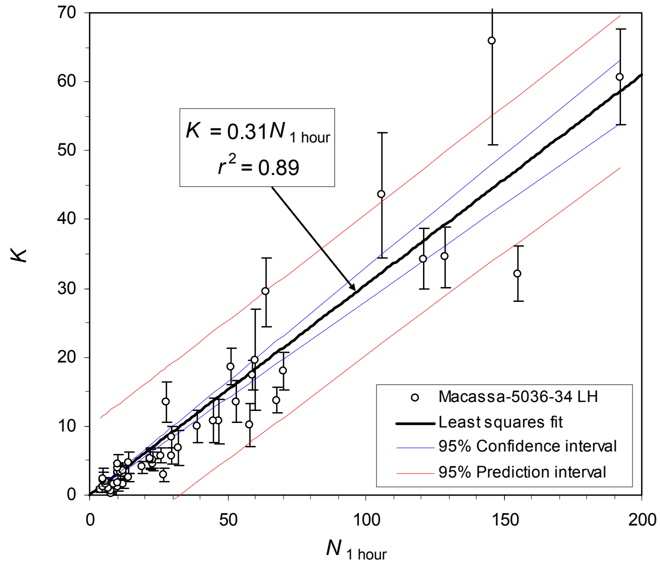

Figure 5. Relationship between K and $N_{1\ \text{hour}}$ for the Macassa site.

Note that the significance of the above relationship depends mainly on the sensitivity of the monitoring system in locating events during the first hour. This is in general ensured if the power-law process is established during the first hour, which based on our analysis (see Fig. 3) occurred in 98% of the cases analyzed. By not considering the cases that satisfy $T_S>1$ and $\kappa>1$, we found that the parameter κ has a surprisingly narrow range, between 0.25 and 0.50, with an average of 0.35±0.07 (see Table 3 for details).

Table 3. Determined activity constant κ with their associated 95% confidence limit.

Site	κ	r^2
A	0.27±0.05	0.61
Copper Cliff North	0.39±0.03	0.85
Craig	0.39±0.06	0.98
Kidd Creek	0.47±0.04	0.75
Macassa	0.31±0.02	0.89
McCreedy East	0.29±0.03	0.89
Williams	0.37±0.06	0.83

7 RE-ENTRY PROTOCOL DEVELOPMENT

The formal statistical analysis performed by Vallejos & McKinnon (2009) demonstrated that the MOL equation can be adequately used to describe the event decay rate of mining-induced after-shock sequences. Since the analysis was done with c=0, only two parameters need to be specified: p and K. These findings enable us to develop a real time re-entry protocol, as follows:

1) The most probable p value can be assumed.
2) Following the principal event, and after recording the number of seismic events during the first hour, the value of K can be established.

These guidelines provide an approach for delineating an expected decay rate using the MOL equation. Next, we present and discuss two re-entry criteria, used for short and long term decay.

7.1 *Short term decay*

The power-law form of Equation (1) indicates that there is no characteristic time scale and, for large time (t>>*c*), the equation is temporally self-similar (Ito & Matsuzaki, 1990). However, when the MOL curvature is traced in time, a characteristic point emerges at the maximum curvature, given by:

$$T_{MC} = \left[Kp\sqrt{\frac{2p+1}{p+2}} \right]^{\frac{1}{p+1}} - c \tag{7}$$

which depends exclusively on the estimated MOL parameters. The maximum curvature point has the interesting property that it defines the transition between the highest to lowest rate change (Vallejos & McKinnon, 2009).

Equation (7) suggests a possible correlation between T_{MC} and $N_{1\,\text{hour}}$. By replacing Equation (6) in (7) for a power-law process we obtain:

$$T_{MC} = aN_{1\,\text{hour}}^{b} \tag{8}$$

where *a* and *b* are two alternative parameters:

$$a = \left[\kappa p\sqrt{\frac{2p+1}{p+2}} \right]^{b} \tag{9}$$

$$b = \frac{1}{1+p} \tag{10}$$

Table 4 presents the results of the least squares fitting between T_{MC} and $N_{1\,\text{hour}}$ for all the sites analyzed, an example is presented in Figure 6 for the Kidd Creek mine. Note that the coefficient of determination has improved for these relationships compared to those provided in Table 3. Again we found narrow ranges for the parameters *a* and *b*, between 0.20 and 0.55, and 0.50 to 0.80, with an average of 0.38±0.11 and 0.61±0.09, respectively. This correlation has the main advantage that T_{MC} can be estimated without specifying a value of the decay constant *p*.

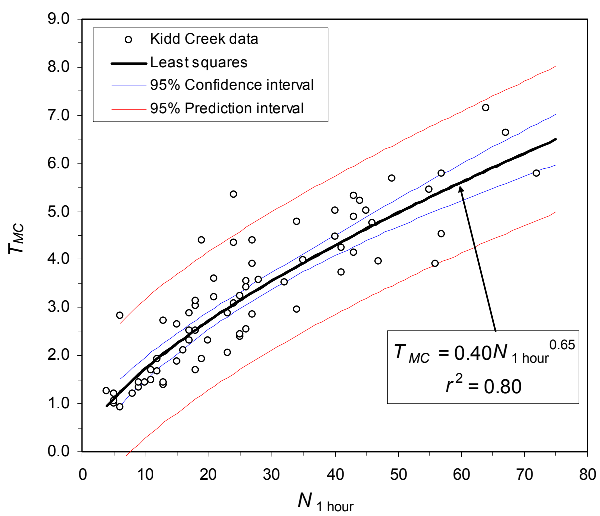

Figure 6. Relationship between T_{MC} and $N_{1\,\text{hour}}$ for the Kidd Creek site.

Table 4. Determined constants *a* and *b* with their associated 95% confidence limit.

Site	*a*	*b*	r^2
A	0.47±0.18	0.53±0.10	0.81
Copper Cliff North	0.20±0.05	0.79±0.06	0.93
Craig	0.30±0.23	0.66±0.16	0.99
Kidd Creek	0.40±0.13	0.65±0.09	0.80
Macassa	0.39±0.09	0.57±0.05	0.92
McCreedy East	0.39±0.11	0.57±0.08	0.92
Williams	0.53±0.27	0.53±0.11	0.82

7.2 *Long term decay*

Another application of the MOL equation for re-entry purposes is to define re-entry as the time required for the MOL to decay to a previously defined rate or background level B:

$$T_{LT} = \left[\frac{K}{B}\right]^{\frac{1}{p}} - c \tag{11}$$

If B can be appropriately defined, and if the estimated rate at T_{MC} is higher than B, then Equation (11) can be used for estimating long term decay.

7.3 *Application example*

We make use of the case presented in Figure 1 to illustrate the concepts and applicability of the proposed guidelines. This aftershock sequence was triggered by 1.6 Nuttli magnitude event and has $N_{1\ hour}$=64 events with M_Z=-2.1 (see Fig. 7). Using a predefined background rate of B=2 events/hour and the aftershock statistics of the Kidd Creek complex we obtain:

- p=1.04
- $K = 0.47 \times 64$ =30.1
- $T_{MC}^{(average)} = 0.34 \times 64^{0.69}$ =5.9 hours
- $T_{MC}^{(95\%\ P.I.)}$ =7.4 hours
- T_{LT}=$(30.1/2)^{1/1.04}$=13.6 hours

It can be seen from Figure 7 that the calculated rate for this sequence has decayed to 4.7 events/hour during the first 6.0 hours, while it takes an additionally 7.5 hours to decay to the predefined background rate of 2.0 events/hour. Note that the estimates were made using only the measured number of events during the first hour after the main event as an input parameter. Because the correlations for T_{MC} were obtained for single aftershock sequences, a background time window should be considered in addition to the estimated $T_{MC}^{(average)}$. This can be easily defined by using the statistical variability of the data. By using Figure 6 with $N_{1\ hour}$=64 events and a 95% prediction interval we obtain $T_{MC}^{(95\%\ P.I.)}$= 7.4 hours, i.e., the variability of the data suggests waiting at least 1.5 hours after the $T_{MC}^{(average)}$ to include 95% of the cases. Note that in this case, a secondary aftershock sequence appeared during the background time window which resets the re-entry clock and the restriction continues to at least hour 10.5. Given the appearance of this secondary aftershock sequence during the background time window it seems appropriate to delay re-entry until the long term decay is reached, i.e. until hour 13.6.

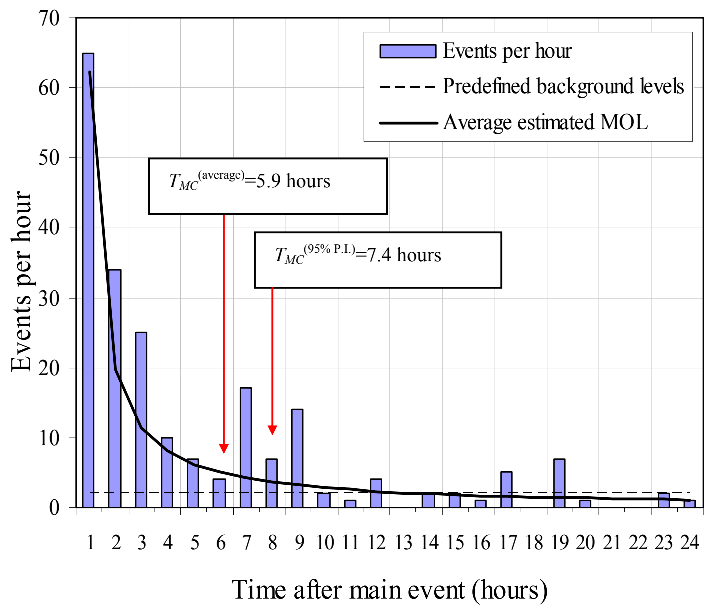

Figure 7. Re-entry protocol development for a 1.6 Nuttli magnitude event using the proposed guidelines.

8 CONCLUSIONS

Using a rigorous statistical approach and the modified Omori's law for the decay of aftershock rate $n(t) = K/(c+t)^p$ we have proposed practical guidelines for the estimation of a re-entry time after large events/blasts in seismically active mines. After analyzing 252 mining-induced aftershock sequences we concluded the following regarding the parameters *c*, *p* and *K*: Consistent parameters are obtained if the Omori formula is fitted to the time interval that satisfies power-law behaviour (c=0). The *p* value seems to vary from sequence to sequence, most (98%) falling within a typical range of 0.4-1.6. The parameter *K* can be adequately expressed as: $K=\kappa N_{1hour}$, where κ is a site specific parameter, and N_{1hour} is the measured number of events occurring during the first hour after the principal event. We presented two different re-entry criteria for short and long term decay. We found that the short term decay criterion T_{MC} can be estimated by the expression: $T_{MC} = aN_{1hour}^{b}$, where *a* and *b* are two parameters dependent on local conditions. The variability of the data at each site enables us to estimate a background time window or "factor of safety" to be used after T_{MC} and before re-entering the area. The parameters of the MOL used in the guidelines are site specific, however, they presented a particularly narrow range for seven different mine sites in Ontario: κ ranges between 0.30 and 0.50, *a* between 0.2 and 0.55, and *b* between 0.5 and 0.8. These narrow ranges make it practical to use them as a basis for parameter estimation in new situations.

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