



Observed spatial and temporal behaviour of seismic rock mass response to blasting

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Synopsis

Seismically active mines generally experience an increase in seismic hazard due to rock mass instability following blasting. Re-entry protocols commonly include measures to limit the spatial and temporal exposure of personnel to increased seismic hazard induced by blasting. The management of periods of increased seismic hazard requires the development of re-entry protocols for a unique mining environment. Identifying mining conditions that may result in significant seismicity following blasting relies on retrospective analysis, which is often focused on seismicity occurring within a certain period after blasting and within a certain radius of the blast in the broader context of site-specific experience.

The analysis of seismicity without considering blasting times and locations allows for the relationship between seismicity and blasting to be investigated without prior assumptions concerning dependency. To achieve independent analysis, seismicity that is clustered in space and time (referred to as a seismic sequence) must be identified by assessment utilizing only seismic parameters. An automated algorithm is implemented that assesses the timing, location, and quantity of seismicity to identify seismic sequences, represented by the time of the first event and mean location of all events in the sequence.

The relationship between sequences and blasts is assessed by calculating the distance and time from each sequence to the closest blast in space and time. Establishing an independent classification between sequences and blasting provides insight into the unique cases where seismic sequences are remote and/or delayed with respect to blasts and identifies cases when sequences exhibit a weak relation to blasting. The nature of seismic responses to blasting has direct implications for the management of the increased seismic hazard associated with seismic sequences.

The approach presented in this study contributes to the management of seismic hazard by providing empirical support for the relationship between seismic sequences and blasting. These relationships indicate the portions of sequences that can and cannot be practically managed using tactical approaches. Furthermore, the analysis of sequences reveals the nature and evolution of rock mass responses to blasting. These results have implications for the extent of spatial or temporal re-entry restrictions required for the optimal management of time-dependent rock mass response to mining.

Keywords

blasting, mining-induced seismicity, clustering, seismic sequence.

Introduction

Seismicity in a mining environment exhibits a range of spatial and temporal behaviour due to varying contributions of, and complex interplay between the factors that contribute to a seismic response (Hudyma, 2008). These

factors can vary significantly depending on the mining environment, and include rock mass characteristics, geological structures, mining methods, mining sequence, and *in situ* and mining-induced stresses.

Increased rates of seismicity are spatially controlled within the mining environment, commonly exhibiting spatial clustering associated with sources of seismicity (pillars, abutments, faults *etc.*) and rock mass failure surrounding localized stress changes. Assessment of the spatial and temporal characteristics of seismicity contribute to understanding the timing, location, and magnitude of seismic hazard, which operations aim to manage using various strategic and tactical approaches (Hudyma, 2008; Cho *et al.*, 2010). Elevated rates of seismicity in a mining environment are commonly observed following significant changes in stress conditions, lasting in the order of hours to days (Kgarume, Spottiswoode, and Durrheim, 2010; Vallejos and McKinnon, 2008).

Management of increased seismic hazard associated with an elevated rate of seismicity aims to reduce seismic risk through minimizing workforce exposure (Vallejos and McKinnon, 2008; Penney, 2011). This tactic requires an exclusion period and volume to be defined for various mining conditions, commonly referred to as a re-entry protocol. Re-entry protocols are site-specific time and space limitations that aim to minimize workforce exposure to elevated seismic hazard. These protocols are developed using a number of retrospective methods and validated using reactive analysis.

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The iterative sequence identification method presented in this paper allows responses to be assessed independently of blasting information. This allows the space-time relationship between seismicity and blasting to be assessed, contributing additional information to the development of re-entry protocols centred on the location and time of blasting. The method aims to identify various permutations of seismic responses to blasting. However, it does not attempt to address directly the seismic hazard and risk associated with these responses.

The mine that is considered in this study is a sublevel and open stoping operation that blasts at the end of 12-hour shifts. The size of development blasts is approximately 350 t while the size of production blasts ranges from 1000 t to 10 000 t.

Management of seismic hazard using re-entry protocols

Site-specific experience of personnel plays a significant role in the management of seismic risk following blasting through contributions to re-entry decisions. Hudyma (2008) suggests that subjective decisions based on local experience form the basis of workplace closure and re-entry practice. This topic is also discussed by Larsson (2004), outlining that most standard re-entry procedures require the contribution of experience from ground control engineers and management to final decisions. Vallejos and McKinnon (2008) found, in a survey of 18 seismically active mines, that re-entry protocols in over 70% of these mines were based on local experience, due to variation in seismic responses over a range of mining environments. Penney (2011) notes that expected re-entry times (derived from retrospective analysis) are considered minimum requirements, with site experience contributing to justifying extended re-entry times. Examples of such cases are continued elevated seismicity, irregular seismicity, or the occurrence of a significant magnitude seismic event late in the re-entry period.

Although valuable insight gained through site experience is important in managing seismic hazard, there are clear dangers associated with relying too heavily on unquantified personal impressions and interpretations. Mendecki (2008) discusses this topic in a broader context, suggesting that the use of human judgment to reduce complexities in the assessment of probabilities associated with seismic hazard may be subject to limitations of experience, interpretation, and motivational biases. An indispensable tool to combat over-reliance on subjective approaches is the use of quantitative techniques to assess the seismic response to blasting.

The use of retrospective assessment of seismicity clustered in space and time to develop re-entry protocols originates mainly from the study of aftershocks following large earthquakes. For the purpose of this paper, seismicity that is temporally transient and is closely related in space and time to preceding seismicity is referred to as a *seismic sequence*.

Seismic sequences have been studied in a wide range of mining environments and have been well described by the Modified Omori Law (MOL), originally developed in crustal studies (Omori, 1894; Utsu, 1961). Additional assessment methods have been implemented, such as the analysis of seismic parameter rates, event rates, and cumulative event

counts. Studies that have investigated the temporal characteristics of seismic sequences following blasting or large-magnitude events include those of Malek and Leslie (2006), Heal (2007), Kgarume (2010), Vallejos and McKinnon (2010), Naoi *et al.* (2011), and Penney (2011).

Spatial behaviour of seismic responses with time is variable, with the seismicity either being constrained to the location of the stress change (Heal, 2007; Plenkers *et al.*, 2010) or in some cases becoming spatially widespread over time (Kgarume, 2010; Eremenko *et al.*, 2009). Hudyma (2008) notes that seismic responses are spatially related to blasting, although the original seismic response may cause seismicity associated with additional rock mass failure processes (*e.g.* fault deformation).

Generally, in a mining environment, identification of seismic sequences is based on an initial stress change related to blasting or large seismic events. Analyses are performed by implementing variations of a simple space-time window surrounding blasts or large-magnitude events to define an ensuing seismic sequence. Figure 1 illustrates the implementation of a space-time window with a radius and period defining the boundary for consideration in the respective domains. The events that occur in this volume and time period are included in the sequence (blue circles), while those that fail one or both of these criteria are excluded from the sequence (green circles).

This approach requires an accurate point in space and time to define the origin of a space-time window. The portion of sequence events captured depends on the space-time window size. Larger windows include a greater portion of 'false' background events, while a smaller window may exclude sequence events (Molchan and Dmitrieva 1992). Baiesi and Paczuski (2004) noted that while space-time windows can omit sequence events, the method generally performs well for large earthquakes.

This sentiment appears to be shared throughout the mining industry, evident from the widespread application of space-time windows to assess seismic sequences. Examples in mining where a space-time window is used to assess seismicity after blasting or large seismic events include Heal, Hudyma, and Vezina (2005), Heal (2007), Kgarume (2010), Kwiatak (2004), Richardson (2002), Hudyma (2008), and Eremenko *et al.* (2009).

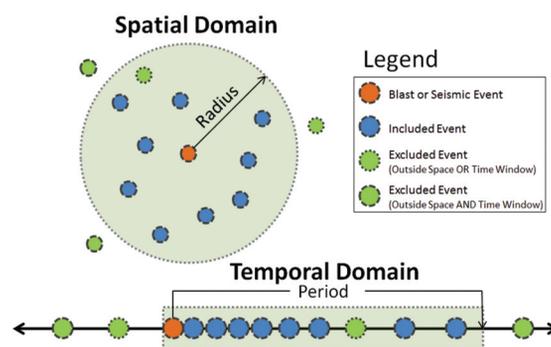


Figure 1—Representation of a seismic sequence definition using a space-time window following a blast or seismic event (orange), with respect to included events (blue) and excluded events (green). The spatial domain shows the location of events with respect to an analysis volume (top). The temporal domain shows the timing of events with respect to an analysis period (bottom)

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The use of space-time windows centred on the location of a blast or large seismic event may be adequate for many re-entry applications. However, the definition of spatial and temporal limits used in analysis can be sensitive to variation in seismic occurrence. The location of sources of seismicity may significantly influence the location of seismic responses and result in a spatial offset to blasting. Moreover, temporal variation may occur due to time-dependent stress redistribution such as the occurrence of a large seismic event within a response. Spatial and temporal variation results in re-entry criteria becoming increasingly dependent on the broader analysis of seismicity and site-specific experience to manage seismic hazard with tactical approaches.

Figure 2 illustrates the sensitivity of analysis to the definition of a space-time window for a well-located seismic database. For an individual blast, a space-time window of radius 75 m is implemented for spatial (3D view) and of 4 hours duration for temporal analysis (time series). Relatively few events pass this criterion, which results in the interpretation of a weak seismic response (Figure 2a). By expanding the radial criterion to 100 m, additional events are included in the analysis, which indicates a strong spatial and temporal response that may be related to a geological structure (Figure 2b). Increasing the radial criterion further to 125 m (Figure 2c), more events are included in the response to blasting. This response has a strong planar orientation and a consistent temporal decay, which may indicate that blasting has altered stress conditions of the fault, resulting in deformation.

There is a significant difference between the tactical management of a low seismic hazard response (*e.g.* a few small events) and a high seismic hazard response (*e.g.* larger events generated by geological structures). The latter response requires increased spatial and temporal exclusions to account for higher seismic hazard following blasting. In addition to the outcomes for re-entry protocols, the

interpretation of these responses may have broader implications for mining operations. Examples include the management of future mining sequences that may result in similar seismic responses, planning of production to account for longer re-entry requirements, and optimization of ground support requirements. The definition of the space-time window for individual responses can significantly influence outcomes of the re-entry analysis; therefore, an assessment of the space-time characteristics of seismicity is essential for the management of seismic hazard.

Space-time analysis of seismicity

In the discussion of spatial and temporal characteristics of seismic sequences it is necessary to clearly define two causative modes of seismicity derived from the study of naturally occurring tectonic earthquakes and seismicity caused by human activities (McGarr and Simpson, 1997; McGarr, Simpson, and Seeber, 2002; Hudyma, 2008):

- *Induced seismicity*—causative stress changes are greater than or proportional to the resultant seismic response. For example, a localized response to stresses induced by blasting
- *Triggered seismicity*—causative stress changes are significantly less than the resultant seismic response. For example, remote seismic response from geological features to stresses induced by blasting.

Understanding when and where induced and triggered modes of seismicity occur has important implications for the appropriate management plan. This information may be used to help understand when and where seismic responses can be expected relative to the extent of induced stresses. Assessing this information with respect to the rock mass characteristics, induced stresses, stress transfer mechanisms, and seismic responses can give further insight into how and why these modes of seismic responses occur. Improved and verified

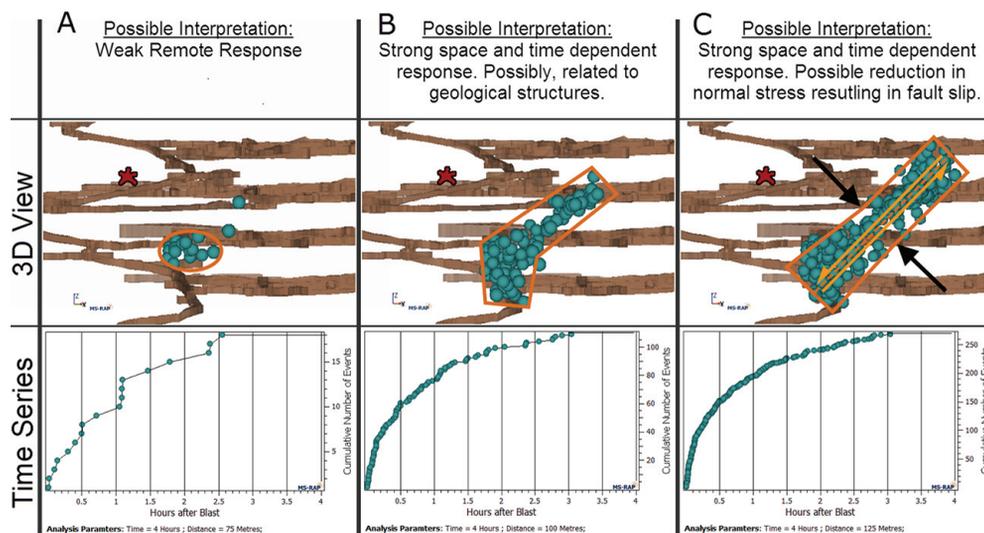


Figure 2—Example of a seismic response following blasting which shows the potential for analysis interpretation to be sensitive to the definition of spatial criteria used to define events following blasting. Three radial distances are considered, increasing from 75 m (Figure 2a) to 125 m (Figure 2c), resulting in a greater portion of the response being captured in space (3D view) and time (time series). As a result, an increasingly comprehensive interpretation of rock mass failure can be achieved (possible interpretation)

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understanding of rock mass response to mining is important, not only for the short-term management of seismicity but in contributing to longer term management strategies.

Identifying seismic sequences is an ambiguous task that is largely dependent on the study aims (Molchan and Dmitrieva, 1992). The reliable detection of seismic sequences depends on the contrast between a seismic sequence's spatial and temporal properties compared to background seismicity. If it is assumed that seismic sequences are finite periods of seismicity clustered in space and mixed with background seismicity, it becomes impossible to completely separate the two without error (Molchan and Dmitrieva, 1992).

Sequence identification becomes increasingly involved when aiming to account for complexities in a mining environment. The practice of blasting at designated times (typically at the end of working shifts) inevitably results in seismic sequences overlapping in time and separated in space. Furthermore, blasting in similar spatial locations may result in sequences overlapping in space but not in time. Additionally, stress redistribution mechanisms may result in a significant degree of variability in the space-time relationship to an initial stress change. In a mining environment where several blasts may occur simultaneously, it may not be possible to associate a seismic sequence with any one major stress change (Heal, 2007). Comprehensive seismic sequence identification methods should allow for the recognition of remote and/or delayed sequences that may overlap in space or time without relying on a known significant stress change.

The most appropriate solution for sequence delineation aims to maximize the number and completeness of seismic sequences identified while minimizing the number of background events that by chance form false sequences (Molchan and Dmitrieva, 1992). Automated algorithms that assess spatial and temporal relationship between seismic events present an attractive option to extract information concerning timing and locations of seismic sequences. The study of seismicity related to mining and earthquakes has resulted in a number of approaches to the assessment of sequences.

Temporal identification methods include the assessment by Bottiglieri *et al.* (2009) of a ratio between standard deviation and average value of the successive inter-occurrence time within a non-overlapping time window. Additionally, Frohlich and Davis (1985) assess a ratio between the occurrence time of the origin event and the following and preceding events to determine if a sequence of events is generated by a stationary Poisson process to a certain confidence. These methods, and other solely temporal methods, do not consider the spatial distribution of the seismicity and, therefore, seismicity that occurs dispersed throughout space is considered equally with seismicity that exhibits strong spatial clustering.

Depending on the application and focus of analysis, it may be sufficient to represent the spatial and temporal characteristics of clustered seismicity by a single numerical value, for example, Single Link Cluster and Thirulamai Mountain metrics (Cho *et al.*, 2010; Kijko and Funk, 1996; Matsumura, 1984). The use of a single measure of seismicity has been avoided in the identification of seismic sequences, as these methods do not allow full flexibility when a contrast

in spatial and temporal correlations exists. Conceptually, metrics will result in the same measure for the following cases:

1. A strong temporal correlation, although a weak spatial correlation
2. A strong spatial correlation, although a weak temporal correlation
3. A moderate spatial and temporal correlation.

The use of metrics is undesirable due to the inherent nature of routine mining activities that may cause multiple simultaneous sequences throughout the mining volume (metric correlation case 1). Furthermore, multiple sequences may be induced in the same spatial volume due to the progressive nature of blasting (metric correlation case 2). Spatial and temporal attributes of seismicity must be considered independently to allow full flexibility when considering non-seismic causation and remote or delayed sequences.

Several reviewed methodologies also make assumptions pertaining to the statistical nature of sequences, for example, power-law distributions of magnitude, Modified Omori Law (MOL) decays, Stationary Poisson processes, or Ergodic periods (Molchan and Dmitrieva, 1992; Frohlich and Davis, 1985; Baiesi and Paczuski, 2004; Cho *et al.*, 2010). Earthquake aftershock occurrences have been shown to follow these statistical observations, which have in some cases been shown to be applicable to a mining environment (Hudyma, 2008; Vallejos and McKinnon, 2010).

Suboptimal identification methods may result from the adoption of parametric approaches that do not appropriately represent the spatial and temporal attributes of seismicity. The identification of seismic sequences should minimize *unnecessary* assumptions concerning event distributions and associated parameters. Assuming a spatial or temporal event distribution is valuable in subsequent analysis to delineate and quantify sequences once a sequence has been identified. Spatial and temporal modelling provides additional information concerning the attributes of seismicity. For example, temporal modelling of sequences with the MOL allows for the quantification and delineation of time-dependent seismicity that follows a power law decay. Assuming this temporal distribution of events following the identification of a seismic sequence allows for the structured assessment of suitability of fit and parametric uncertainties.

A method for identifying sequences of seismicity is implemented, giving consideration to the requirements identified for an algorithm to be effective in a mining environment. The following considerations were identified from a review of the relevant literature:

- ▶ *Avoid the use of information outside of the seismic database.* This allows for the independent assessment of the influence of changes in stress conditions on the spatial and temporal occurrence of seismicity
- ▶ *Account for spatial or temporal superimposition.* The approach should identify sequences that overlap in time (for example, blasting multiple areas of the mine concurrently) or space (for example, stationary sources of seismicity)
- ▶ *Disregard magnitude of events.* Stress changes may be due to large seismic events; however, they may also be

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a result of blasting and other mining activities. A large seismic event may not initiate a sequence and, therefore, should not influence the identification of a sequence

- ▶ *Avoid single measures of clustering.* Allow flexibility to define clusters with different space-time characteristics and avoid misrepresentative correlations between events
- ▶ *Avoid the use of statistical distributions.* Seismic sequences may be variable or have short space and time scales and, therefore, may not conform to statistical distributions
- ▶ *Maximize the number of sequences identified while minimizing the number of false sequences identified.* The method should be insensitive to the degree of spatial and temporal clustering with respect to the characteristics of background seismicity.

Overview of the methods used to identify mining-induced seismic sequences

Relatively complex algorithms are required to identify and delineate seismic sequences while addressing all of the previously stated considerations for the mining environment. The development and documentation of such a method falls outside the scope of this paper. This study provides a limited overview of the methods used to assess seismic sequences associated with the rock mass response to blasting. The following sequence identification method aims to be as simple as possible and, where practical, take into account the previously stated considerations. The critical aspects of the algorithm are discussed in further detail following the method description. The implemented method is summarized in five iterative steps:

- (a) Ensure a clean and consistent seismic database
- (b) Identify the sequence trigger event based on predefined threshold settings. This method implements a combination of space-time windows and moving averages
- (c) Model events following the sequence trigger using a MOL (Omori, 1894; Utsu, 1961; Vallejos and McKinnon, 2010)
- (d) Exclude adequately modelled events from the data-set

- (e) Repeat steps (b) and (c) for increasingly sensitive threshold settings in order to capture weaker sequences. These steps are repeated until no additional sequences can be identified.

The result of this analysis is the definition of a sequence 'trigger'. This trigger has the time of the first event that forms part of the sequence. The trigger location is determined from the mean spatial occurrence of all events that have been modelled by the MOL. Figure 3 shows the definition of a typical sequence trigger for a number of events clustered in space and time. This resultant trigger is represented by a cross and illustrated with a table view (left), cumulative event count time series (centre), and 3D view (right).

Parameters

The algorithm requires the definition of an initial triggering space-time window and an additional modelling space-time window (radial distance and period). This approach improves the accuracy of the initial identification of potential sequences by identifying where and when sequences exhibit the strongest clustering in space and time. The use of a second-pass space-time window allows the modelled sequence to include a wider range of events that are likely to be associated with the process. The selection of these parameters is related to the typical temporal and spatial scales observed in mining. Triggering time windows consider a period of tens of minutes, while the triggering space window is defined by the scale of clustering in the mining environment.

The delineation of a modelled sequence considers the spatial and temporal attributes of seismicity. A simple approach defines sequence events as those occurring within a time interval that is suitably modelled using the MOL, and within a fixed spatial distance from the mean location of the sequence trigger. The spatial distance aims to capture the vast majority of spatially related events and represents the spatial scale of the source of time-dependent seismicity.

The use of fixed spatial distances assumes that events are contained within a spherical volume around the sequence trigger. This assumption is not ideal, as seismicity may cluster as complex geometric shapes. Furthermore, the use of fixed distances is assumed to represent the scale of seismic sources. This assumption may be invalid, as sources of

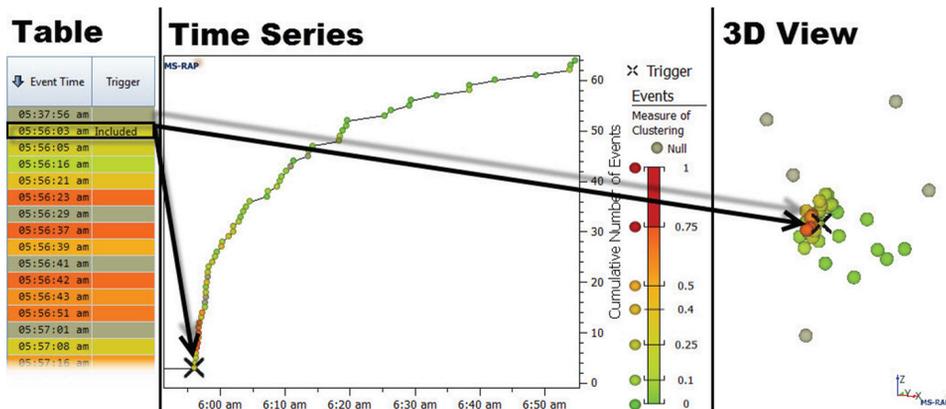


Figure 3—A trigger is defined to be the first event in the sequence with a mean location that is calculated from subsequent events

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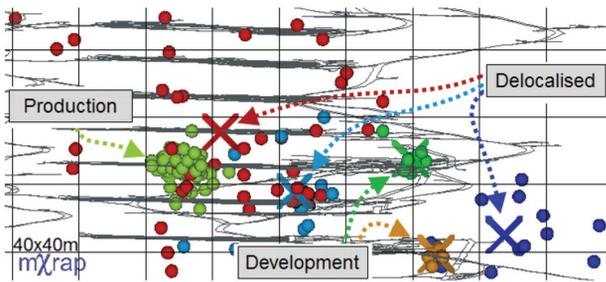


Figure 4—Seismicity occurring over 12 h and related to development blasting (approx. 10 m), production blasting (approx. 40 m), and delocalized stress redistribution (> 100 m)

seismicity evolve during the progression of mining. The definition of distance windows does not consider source parameters, as the spatial extent of clustering is controlled by the scale of seismic sources rather than individual events. While in some cases the scale of seismic sources may be related to the scale of a causative process (e.g. a large event caused by a faulting mechanism), a correlation between source parameters and spatial extent of clustering is not applicable for all rock mass failure mechanisms observed in the mining environment. Sequence delineation can be improved significantly by implementing comprehensive approaches to spatial and temporal modelling.

Despite these major assumptions, the use of fixed spatial distances for spatial delineation is typically effective, as spatial scales of seismicity are related to distinct rock mass failure processes, for example, development blasting (approx. 10 m), production blasting (approx. 40 m), and delocalized stress redistribution (> 100 m) (Figure 4).

Iterative approach

As previously outlined, this method implements an iterative approach that requires the systematic relaxation of the number of events that are required to define a sequence. Multiple passes are taken until no additional sequences can be identified or modelled. An iterative approach allows the algorithm to detect sequences that are spatially or temporally

superimposed. Three theoretical cases of sequence occurrence are illustrated in Figure 5 using synthetically generated seismic data:

1. *Case 1*—sequences occur separately in space and time (blue events)
2. *Case 2*—sequences occur in the same space, although offset temporally. After an initial sequence occurs (orange events), any significant increase in event occurrence (red events) causes the initial sequence to be truncated at this time. Additional iterations detect the delayed increase in event rate, which is identified and modelled
3. *Case 3*—sequences occur simultaneously in time, although offset spatially. During the occurrence of an initial sequence (light green events), another sequence occurs elsewhere in the volume considered (dark green events). During the initial pass, one of these sequences is identified and modelled with an additional iterations identifying and modelling the second sequence.

An iterative approach is taken to improve the overall consistency of sequence identification by allowing for rules based on the number of clustered events to specify identification order. In effect, the algorithm prioritizes sequences containing more events over sequences containing fewer events, while still allowing relatively smaller sequences to be identified. This functionality is important when considering the scale of responses that may be present within a data-set and accounting for cases where smaller sequences may exist within larger responses. Smaller sequences are identified only if the larger responses cannot be adequately modelled, which prevents inconsistent segmentation of larger sequences.

Figure 6 shows the use of event count criteria to achieve an iterative functionality through application to synthetically generated seismic data. A case is considered where three sequences occur with similar event count relative to the background rates. The iterative approach identifies the three sequences separately, despite the second and third sequences occurring within the same initial modelling time window (24 hours) after the first sequence (left). Moreover, the use of

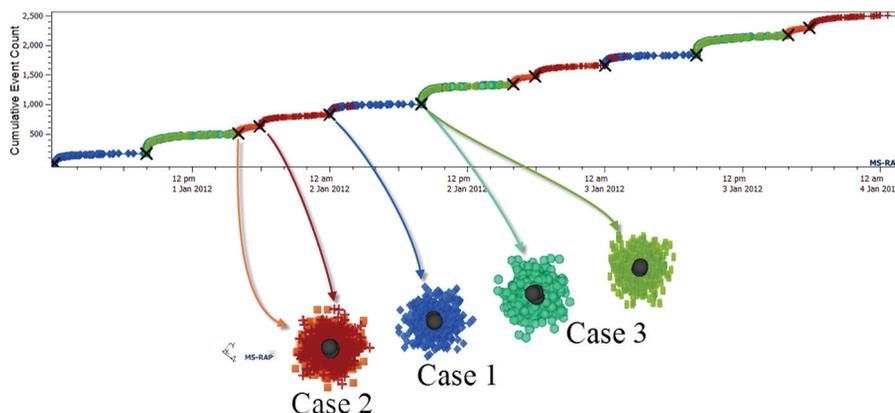


Figure 5—An iterative approach accounts for several spatial and temporal cases of sequence occurrence, illustrated by a time series of the cumulative number of events (top) and 3D view (bottom) for synthetically generated seismic data. Individual sequence separate in space and time (blue); two sequences occurring in the same space that are offset in time (red and orange); and two sequences occurring at the same time that are offset in space (green)

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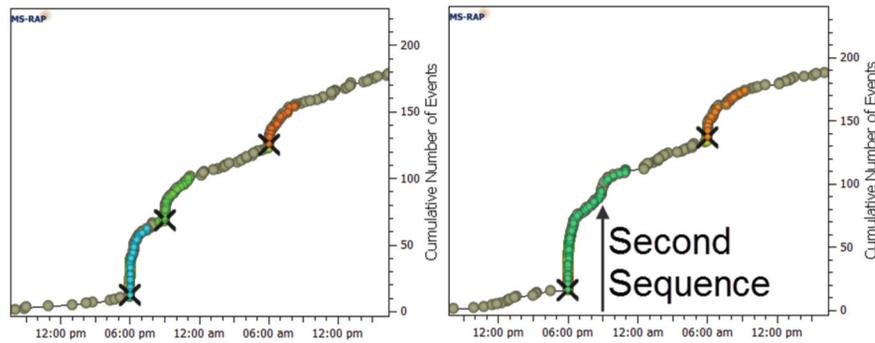


Figure 6—Time series of the cumulative number of events (grey), sequence triggers (crosses), and sequence events (coloured events) for synthetically generated seismic sequences and background seismicity. The iterative approach ensures three sequences separately, despite the second and third sequences occurring within the same initial modelling time window (24 hours) after the first sequence (left). A decreasing count criterion ensures the largest sequences are considered first in the case of insufficient contrast between the seismicity being modelled (right)

decreasing count criteria ensures that the largest sequence is considered first, and therefore if these sequences cannot be separated with confidence they will be modelled as a single sequence.

To illustrate this case, the first sequence is modified to have a larger event count relative to the second sequence (start shown with an arrow), resulting in an insufficient contrast between the two sequences, and hence these sequences are modelled as one (right). Note that the location of these events is not considered in this example; however, if the second sequence were separate in space, the iterative approach would allow this sequence to be identified separately despite a seemingly weak temporal occurrence.

Seismic sequences and blasting

Analysis of the space-time occurrence of seismic sequences can be combined with sources of additional information to achieve further insight into seismicity. Information may include the seismic database, for example, magnitude of the event preceding a sequence, or information pertaining to mining operations, for example, blasting records or volume mined.

Analysis of seismic sequences makes an essential contribution to the tactical and strategic management of seismic hazard through an improved and validated understanding of the conditions that may result in a seismic sequence. Although there are broad applications for different kind of analyses, this paper focuses on the relationship between seismic sequences and blasting in a mining environment. For this purpose, we define four cases that characterize the space-time relationship between the location and timing of the sequence and the location and time of the blast (Table I).

The relationship between sequences and blasts is arbitrarily defined by considering the spatial influence of blasting, scale of sources of seismicity in the mining environment, timing and location accuracy of blast records, and performance of the seismic array. For example, a sequence must occur more than 50 m away from a blast to be considered 'remote' and 1 hour after a blast to be considered 'delayed'. Sequences occurring outside 200 m or 6 hours are considered 'remote or delayed'. An example of sequence classifications is shown in Figure 7, displaying cumulative

count with time and a perspective view of seismicity for a given period. Three distinctly different responses are shown:

- *Local and immediate sequence*—a sequence occurs on 3 February at 6:30 am (green arrow and markers). This sequence is closely related to blasting

Table I

Descriptions of the four cases characterizing the relationship between a seismic sequence and a blast based on the space-time relationship. Conceptual diagram of cases is shown by an initial stress change represented by an orange splash, initial seismic sequence represented by red circles, and delayed/remote seismic sequences represented by green circles

Case	Description	Conceptual Diagram
Local & Immediate	<p>Case: An immediate seismic response is limited to volume subjected to initial stress change.</p> <p>Cause: "Typical" case of induced seismicity associated with blasting and large seismic events.</p>	<p>Local & Immediate</p>
Remote & Immediate	<p>Case: Seismicity has increased in a volume remote to the primary stress change.</p> <p>Cause: Volumes of rock mass close failure responded to a remote stress change resulting in a triggered response.</p>	<p>Remote & Immediate</p>
Local & Delayed	<p>Case: Seismicity has increased abruptly after some delay in the volume of rock mass subjected to the initial stress change.</p> <p>Cause: Superimposition of time dependent stress redistribution processes. Stress redistribution due to large seismic events within a local & immediate response.</p>	<p>Local & Delayed</p>
Remote & Delayed	<p>Case: Sequence occurs in a volume remote & delayed to the initial stress change.</p> <p>Cause: It is not possible to relate the sequence to a stress change with any significant confidence.</p>	<p>Remote & Delayed</p>

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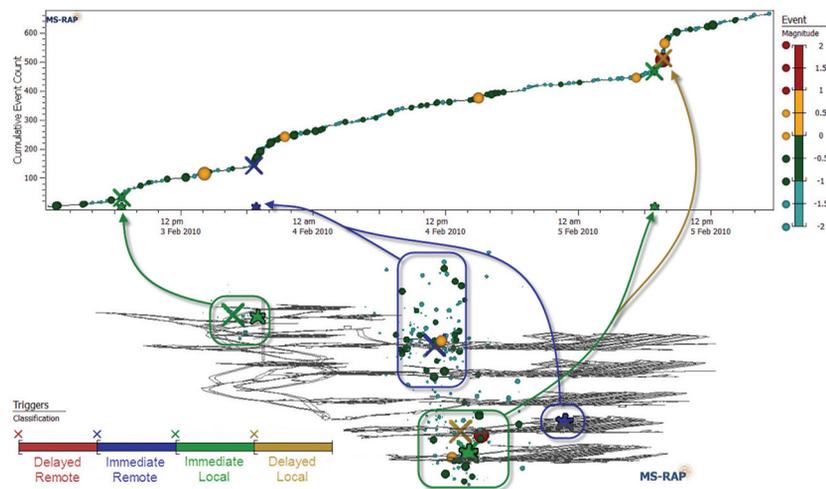


Figure 7—Cumulative count plot (top) and a perspective view of seismicity (bottom). Data over this short period illustrates the variable space-time relationship between sequences and blasting

- Remote sequence—a sequence occurs on 3 February at 6:30 pm (blue arrows and markers). This remote sequence is identified at the same time as a blast, but 130 m away. The occurrence of a remote instability associated with blasting justifies the extension of spatial re-entry exclusions
- Delayed sequence—a delayed sequence occurs with a large event (brown arrow and markers) following a local and immediate sequence to blasting (green arrow and markers) associated with blasting. The occurrence of a delay sequence indicates further stress redistribution and justifies the extension of temporal re-entry exclusions.

Proportionality of sequence classifications

The assessment of the sequence classification proportionality determines what percentage of identified sequences fall into each classification and provides an indication of the sources of seismicity that may be present in a particular mining environment.

Table II provides the proportional counts of sequence classifications for two Western Australian mines. At Mine 1 (a narrow-vein stoping operation), a significant majority (78%) of all sequences occur locally and immediately after blasting with low proportions of remote or delayed responses to blasting. These conditions can be analysed using the traditional 'time after and distance from blasting' approaches. In comparison, Mine 2 (a sublevel caving operation) experiences only 32% of all sequences locally and immediately after blasting, indicating that sequences are influenced by relatively more complex stress conditions. This interpretation is supported by 16% of all sequences occurring remotely and immediately after blasting (compared to none for Mine 1), indicating that volumes of rock mass close to failure may be influenced by remote blasting. As a result, Mine 2 may require an approach to re-entry protocols that places greater emphasis on spatial aspects of seismicity; in particular, the responses of geological and geometrical defined sources of seismicity.

Table II also provides an indication of the remote and delayed sequences that occur for each of these cases. At Mine 1, 18% of sequences are not associated with any specific blasting. However, at Mine 2, 47% of sequences occur outside blasting space and time. Seismic hazard associated with these sequences cannot be managed with re-entry protocols, and therefore an increased emphasis on other risk mitigation approaches may be required for Mine 2.

The proportional measure of the sequences provides an indication of the proportion of spatially and temporally clustered seismicity that is closely related to blasting and, therefore, can be expected to be captured using re-entry protocols. Sequences that are not directly related to blasting will likely require management using extensive tactical methods (e.g. increased spatial and/or temporal exclusions) and complementary control approaches. Even if the underlying seismic hazard associated with remote or delayed sequences is similar to that for local and immediate sequences, seismic risk will be elevated if these cases are not accounted for by the tactical management of hazard. Furthermore, proportional representation indicates to what degree geological structures and/or stress redistribution mechanisms may influence the management of seismic hazard following blasting.

Time dependency of sequence classifications

The progressive influence of mining can be examined through the accumulation of individual sequences over time based on the specific sequence classifications. Figure 8 shows

Table II

Proportional counts of sequence classifications for two Western Australian mines

Case	Local and immediate	Remote and immediate	Local and delayed	Remote and delayed
Mine 1	78%	0%	4%	18%
Mine 2	32%	16%	5%	47%

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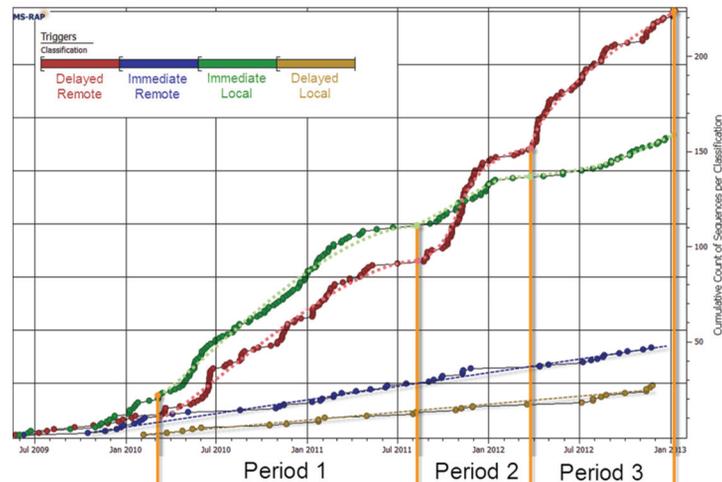


Figure 8—Cumulative count of each individual sequence classification over time. Trends have been drawn for local and immediate sequences (green) and remote and delayed sequences (red) for periods with distinct relative rates of occurrence. Remote and immediate (blue) and local and delayed (brown) sequences follow consistent linear trends

trends in the relative rate of occurrence between sequence classifications, which are described by three periods related to the progression of mining. *Remote and immediate and delayed and local* sequences occur consistently over the time period considered. However, the interpretation is restricted due to the limited data.

- *Period 1*—‘typical’ mining of the established regions in the mine, resulting in proportional generation of seismic sequences closely related to blasting (green) and independent sequences (red) (Figure 8)
- *Period 2*—several new headings are mined, which are oriented perpendicular to the major principal stress direction and in close proximity to geological features. There was a strongly disproportional generation of seismic sequences with significantly more independent sequences (red) occurring relative to those closely related to blasting (green) (Figure 8)
- *Period 3*—the headings mined in the previous period continue to be developed deeper in the mine. The disproportional generation of seismic sequences that was evident from the previous period resumes with more independent sequences (red) occurring relative to those closely related to blasting (green). The discrepancy between the number of independent and blasting-related sequences is not as great as the previous period (Figure 8).

These trends provide an indication of the underlying trends in the spatial and temporal relationship between sequences and blasting and provide inference concerning how the rock mass, particularly geological features, responds to an evolving mining environment. This relationship is essential for understanding how well the seismic hazard can be practically managed by tactical techniques such as re-entry protocols. Furthermore, this information may prove valuable in developing long-term management strategies that seek to minimize similar mining conditions in the future. This could be achieved through actions such as modifying the extraction sequence or increasing ground support in specific areas to reduce the risk from seismic sources that do not respond exclusively to blasting.

Sequences remote from blasting

Retrospective assessment allows for increased confidence in the observation of specific sequence relationships with respect to the mining environment. Consistent occurrence in space and time of *remote and immediate* sequences reduces the probability that *remote and delayed* sequences have been misidentified. Furthermore, consistency allows for increased confidence in the conditions that may result in specific seismic response and hence have the potential to improve the tactical and strategic management.

Figure 9 illustrates a case of spatially concentrated *remote and immediate* sequences that are associated with production and development blasting. There are a significant number of cases of these sequences that centre consistently on a volume of rock mass largely devoid of blasting. Furthermore, sequences are spatially constrained by a volume of rock mass that is defined by a geological contact and the mining geometry, which also experiences high rates of ‘background’ seismicity along with *remote and delayed* sequences.

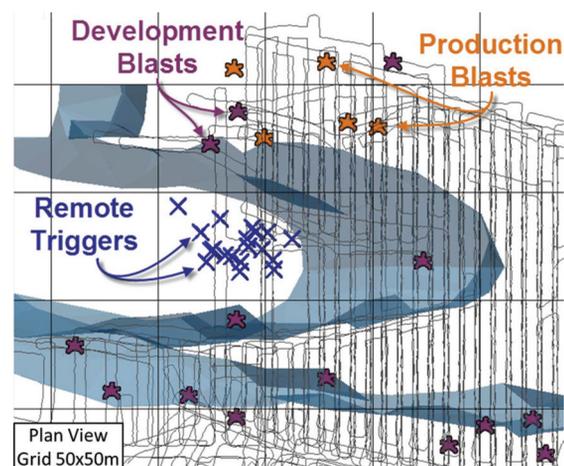


Figure 9—Plan view of remote sequences associated with a geological and geometrical defined source of seismicity (blue crosses), production blasts (orange), and development blasts (purple)

Observed spatial and temporal behaviour of seismic rock mass

The occurrence of sequences and high background rates indicates that the volume of rock mass experiences a stress state close to failure. However, the observation of *remote and immediate* sequences highlights the potential for blasting to influence remotely the stability of this source of seismicity. Seismicity occurring within this volume of rock mass indicates that rock mass stability is sensitive to stress changes 50 m to 200 m away, regardless if the sequence is associated with development (350 t) blasts or relatively larger production blasts (1000 t to 10 000 t).

This rock mass has experienced an extended period of stress state close to failure. Ongoing rock mass failure may be evident from significant background seismicity and the occurrence of seismic sequences, which indicates that a complete yielding process has not occurred and, therefore, remote responses could be expected in the future.

Volumes of the rock mass that respond remotely to blasting require further consideration in the management of seismic risk. This is particularly important if the seismic source poses a high risk and is significant to operations; for example, a fault in close proximity to active workings. In the case of remote responses, re-entry exclusion zones are required to consider the location of blasting with respect to sensitive spatial sources of seismicity in order to ensure that exposure of personnel to seismic hazard is minimized across the entire mining environment. The management of remote sequences should be emphasized when sources of seismicity exhibit signs of experiencing a stress state close to failure; for example, strong responses to blasting and high rates of background seismicity.

Figure 10 examines a prominent source of seismicity over a three-year period. Plotted on a time series is the cumulative event count (left), daily event rate (right), and sequences that have been identified. Furthermore, the figure is annotated with counts of sequence identification during periods of generally similar event rates. In this volume of rock mass, the vast majority of seismic sequences occur during two periods of heightened event rates. Concurrently during these times, a number of *local and immediate* sequences after blasting are identified, along with several *remote and immediate* and *remote and delayed* responses. Management of seismicity

may be improved by combining the assessment of re-entry protocols with medium- to long-term trends in seismicity, such as previous responses to blasting and background rates.

Sequences delayed from blasting

Seismicity that is clustered in space and increases abruptly after a time delay from blasting is identified to be a delayed sequence. Delayed sequences have not been observed to occur without an initial *local and immediate* seismic response to blasting. Two hypothetical physical mechanisms of rock mass failure are proposed that may result in a delayed response following blasting.

The first physical mechanism may result from a time-dependent rock mass failure that contributes to a population of seismic events with a self-similar magnitude distribution. Despite a relatively consistent failure process, variability in the generation of seismicity arises due to further stress redistribution associated with the large event or causative process. A significant increase in the rate of seismicity is observed after the initial sequence, which may be a result of inherent variability associated with this process. Figure 7 provided an example of a blast resulting in a *local and immediate* response (green cross); however, after some time delay there was a response identified with a large event (brown cross).

The second physical mechanism requires the time-dependent initiation of a failure process in addition to the initial time-dependent rock mass failure. The observed response will be a superimposition of the seismicity associated with these two processes. Assuming both processes are the result of the same initial stress change, the additional failure process must be relatively aseismic for a period to observe a delayed seismic response.

Hypothetically, the two physical mechanisms are distinguishable by testing the self-similarity of events through the analysis of seismic source parameters. The initial and delayed sequences must be delineated spatially and temporally in order to test the self-similarity of events. This study focuses on the identification, rather than the delineation, of sequences and therefore, the investigation of the fundamental nature of delayed responses falls outside the scope of this work.

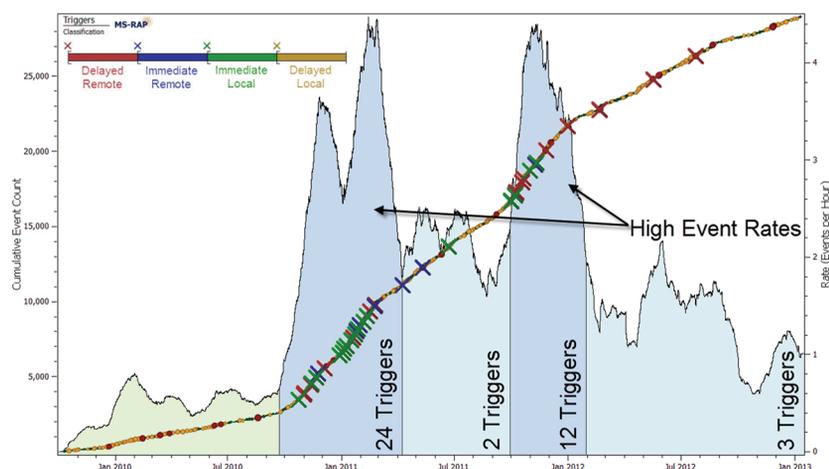


Figure 10—Cumulative event count (left), daily event rate (right) and identified sequences from a prominent source of seismicity over a three-year period. The figure is annotated with counts of triggering during periods of high event rates

Observed spatial and temporal behaviour of seismic rock mass

The major difference between the two physical mechanisms is that the delayed sequence in the first mechanism is due to variability of a single rock mass failure process. In contrast, the second mechanism involves two (or more) underlying processes that result in a seismic response superimposed in space and time. In the latter case, as one or more processes contribute to the generation of seismicity, the self similarity of events may not be maintained, *i.e.* the onset of a second process may result in relatively higher/lower seismic hazard for a given event rate. Figure 11 illustrates the two contrasting physical mechanisms using theoretical cumulative event counts over time. A response associated with the first physical mechanism contributes solely to the observed seismic response, with temporal variability resulting in a delayed sequence being identified (left). In contrast, the second mechanism results in an initial and a secondary response (associated with a fault), which contribute to the superimposition of sequences observed (right).

An observed example of a delayed sequence is illustrated in Figure 12. An initial sequence is located close to blasting in space and time (green cross). A new sequence occurs after 4½ hours due to a spike in event rate that locates close to the first sequence (green cross and brown cross). This second response is considered a *local and delayed* sequence. Irrespective of the underlying mechanism, re-entry management may be required to consider an increased temporal exclusion period due to a renewal of elevated seismic hazard.

Conclusions

Retrospective analysis of the spatial and temporal characteristics of seismicity, together with site-specific experience, underpins the development of re-entry protocols forming the basis for the management of seismic hazard after blasting. Assessment of seismicity clustered in space and time requires the consideration of a number of aspects unique within a mining environment to identify seismic sequences. To satisfy these considerations, a sequence identification method has been developed and applied to real and synthetic seismic data.

Seismic sequences have been classified according to their space-time relationship to blasting and discussed with respect to implications for tactical and strategic management of seismic hazard:

- *Local and immediate*—the sequence occurs close to blasting in space and time. Seismic response to blasting that can be captured by *distance and time* from blasting re-entry criteria
- *Local and delayed*—the sequence occurs close to blasting, although after a time delay. Seismic response to blasting that can be captured by *distance from* blasting re-entry criteria; however, additional considerations are required to determine the temporal extent of the response
- *Remote and immediate*—the sequence occurs after blasting, although remotely in space. Seismic response to blasting that can be captured by *time after* blasting re-entry criteria; however, additional considerations are required to determine the spatial extent of the response
- *Remote and delayed*—the sequence occurs after and remote to blasting. Seismic sequences are not closely related to blasting, and therefore an increased emphasis on other management techniques of seismic hazard is required.

The relative numbers of sequences belonging to these classifications provide an indication of the degree of rock mass inhomogeneity and/or stress redistribution mechanisms that may influence the spatial and temporal relationship between blasting and sequences. Furthermore, the relative rates of sequences belonging to *local and immediate* and *remote and delayed* classifications are linked to the progression of mining, revealing an evolution in seismicity over time. From this analysis, it was evident that the relative numbers of sequences belonging to the four classifications may not be constant for mining environments over space or time.

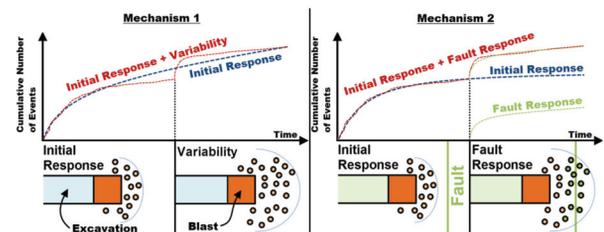


Figure 11—Two physical mechanisms illustrated using theoretical cumulative event counts over time for Mechanism 1: temporal variability of one initial response and Mechanism 2: superimposition of initial and fault responses

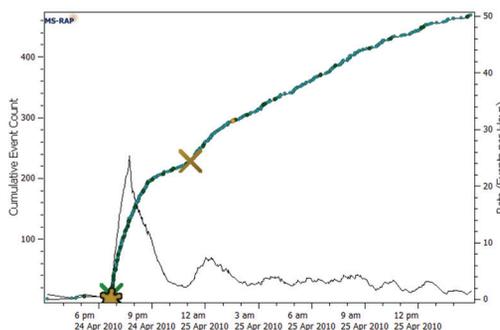
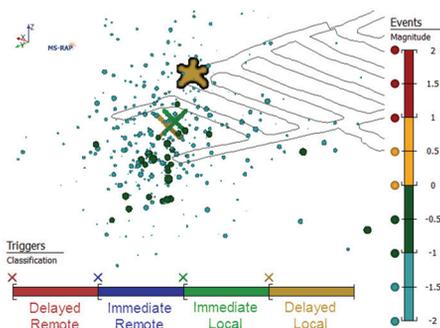


Figure 12—Shown are the cumulative events count, event rate, and time of sequence identifications (left). The modelled events and mean sequence location are shown with respect to mine surveys and blasting (right)



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Analysis of seismicity clustered in space and time reveals the type and evolution of seismic responses to blasting and may benefit the tactical and strategic management of seismic hazard by:

- Providing empirical support for existing re-entry protocols
- Indicating if seismic responses to mining are variable in space and time
- Indicating the required approaches for managing seismic hazard by assessing the:
 - Proportion of sequences that can be practically managed using tactical approaches
 - Portion of sequences that requires extensive tactical methods through the extension of spatial or temporal restrictions
 - Portion of sequences that cannot be practically managed using tactical approaches.

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