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Self-similarity in rock fracturing and the behaviour of large-scale faults in the mining environment

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Seismicity and earthquakes are the consequences of rock mass fracturing. Laboratory testing has been used to simulate rock fracturing mechanisms since the 1960s, including by Mogi (1962), Scholz (1968), Hardy (1972), Hirata, Sato and Iko (1987), Main and Meredith (1989) and Lei et al (1992). These investigations suggest that rock fracturing has similar characteristics on all scales. They also reveal that seismic data contains precursory information that can suggest impending failure. Each of these researchers has used their analysis techniques to investigate large-scale earthquake behaviour; however only limited investigations of mining seismicity have been undertaken to-date.

Morton (2019) has investigated almost 700 failures in the mining environment that are specifically related to large-scale faults. The aim of the analysis was to determine if fracturing data patterns recognised in small scale laboratory samples could be recognised in real-life mining data and if so, could be used to identify failure within the mining environment. Various analysis methods were presented. New techniques were developed to select seismic events specific to selected large-scale structures within the mining environment. This enabled the analysis of the behaviour of these individual structures. Analysis was conducted on temporal variations in event rate, spatial correlation length and b-value, magnitude and energy.

This paper provides a summary of some of the results determined with the research. Analysis of event rate, magnitude and spatial correlation length are provided within this paper. The analysis method and the trends in the each of these parameters will be presented.

INTRODUCTION

The self-similarity characteristics of rock fracturing and the resulting fracturing patterns which appear similar at all scales has been observed since the 1960s. Seismicity and earthquakes are the consequence of rock fracturing. Earthquake scientists have been using laboratory samples to investigate large-scale earthquake behaviours since the 1960s: Mogi (1962), Scholz (1968). These investigations have revealed that the seismic data contains precursory information that can suggest impending failure. Nevertheless, with regard to mining seismic data, only limited investigations have been undertaken to date. Morton (2019) has undertaken investigations into almost 700 failures in the mining environment to determine if any trends can be identified prior to violent failure. These failures comprise 346 instantaneous failures and 347 accelerating slip failures.

Precursor theory
In the 1960s, laboratory experiments were developed to simulate rock fracturing experienced in natural earthquakes (See Mogi (1962), Mogi (1968) and Scholz (1968)). Mogi (1962) was the first to relate acoustic emission studies in rock samples to earthquake studies. He conducted a series of compression and bending tests and measured the acoustic response of the rock samples.

Mogi demonstrated that rock fracturing could indeed be detected, and that frequency of acoustic emissions increased with increasing stress Mogi (1962). He noted that "under the application of constant stress to the heterogeneous medium, a large number of elastic shocks occur, and immediately they begin to decrease gradually, and after some duration, again they begin to increase before the occurrence of the main rupture". This phenomenon is called precursory behaviour.

Scholz (1968) applied acoustic emission sensors to UCS and triaxial rock samples. He observed similar results to Mogi. In the following decades there have been several authors who have conducted acoustic emission testing to investigate different precursory behaviours. These authors include Scholz et al, (1973), Meredith and Atkinson (1983), Main et al (1989), Lockner et al (1991), Lei et al (1992), Lei et al (2000), Lei (2003), Villaescusa et al (2009). Their studies revealed that rock failure occurs in stages and that in each stage the acoustic emission behaviour has distinguishing behaviours.

Stages of failures
Mogi (1962) was the first to note changes in the acoustic emission rate during testing. The results suggest four stages of failure. He describes them as follows:

Stage (1) In this stage, elastic shocks seldom occur, and the stress-strain relation is linear (elastic deformation only take place (sic)).

Stage (2) The frequency of elastic shocks is small, and they take place sporadically.

Stage (3) The occurrence of elastic shocks is remarkable and their frequency increases in proportion to the applied stress. On the other hand, the stress-strain relation deviates from the linearity, that is, the non-elastic deformation is more predominant in this stage.

Stage (4) in the last stage, just before the rupture of the specimen, the frequency of elastic shocks increases more rapidly, and they occur in succession. Microscopically, the main rupture is considered to begin in this stage'.

Scholz (1968) also observed similar behaviour stating that: "At low stress, a flurry of activity occurs; this activity soon dies down to a very low level. At stresses near approximately half the fracture strength, micro fracturing activity begins to build up once more and steadily increases until just before fracture, when a very rapid acceleration of activity occurs". This behaviour is further confirmed by Main et al (1989), Meredith et al (1990), Lei et al (2000), amongst others. Currently, the most accepted theory is that there are three stages of failure; primary, secondary and nucleation.

These phases are characterised by the acoustic emission response of the sample and the physical processes that are assumed to be occurring. In the primary phase, failure occurs at the inter-grain boundaries with frictional sliding and / or compressional failure (closure of cracks) taking place. Lei et al (1992). The secondary phase is characterised by tensile fracturing and an ordering of the fracture pattern into areas of failure. During the nucleation phase, the areas of fracturing merge to form a distinct failure plane with a rapid acceleration in the failure rate as the sample progresses to rupture. Throughout the nucleation phase all modes of failure (compressive, tensile and shear) are represented. A number of signatory behaviours in the acoustic emission response determines each of these phases. The nucleation phase is of most interest to researchers. Identifying the transition from secondary failure to nucleation is critical to understanding rock mass failure.

MINING DATA

Seven sites provided data for the analysis. The data for each site was validated to ensure the calculations within the seismic data were accurate and consistent. Four of the sites had significant errors and validation issues within the seismic data. These issues typically involved the following:

- Blasts not filtered from the event database
- Non-processed data within the event database
- Depth values at extreme distances above and below surface
- Locations outside the mining area
- Inconsistent magnitude calculations.

Fault models were also provided by the sites. These models were validated wherever possible against geological data to ensure accuracy. One site required the fault models to be re-evaluated as small-scale structural features were not joined into obvious larger scale features. Another site's data had to be disregarded as the structural model did not support the structural measurements provided and the validity could not be verified.

DOMAINING PROCESS

To enable analysis of the seismic behaviour of a structure only seismic events associated with the structures must be used in the analysis. Individual datasets for each structure were generated using a domaining method. The method involves offsetting the structure boundaries by a set distance (See Figure 1) to create domain boundaries and extracting all data within the domain. This process was undertaken using a geological software package, Leapfrog™. The distance of the offset was determined numerically based on the density of the data around the fault. This was determined by calculating the distance between structure surface and every event in the database. Statistics were used to determine the distance at which the event concentrations decreased. It was assumed that events occurring at the intersection of structures were associated with both intersecting structures.

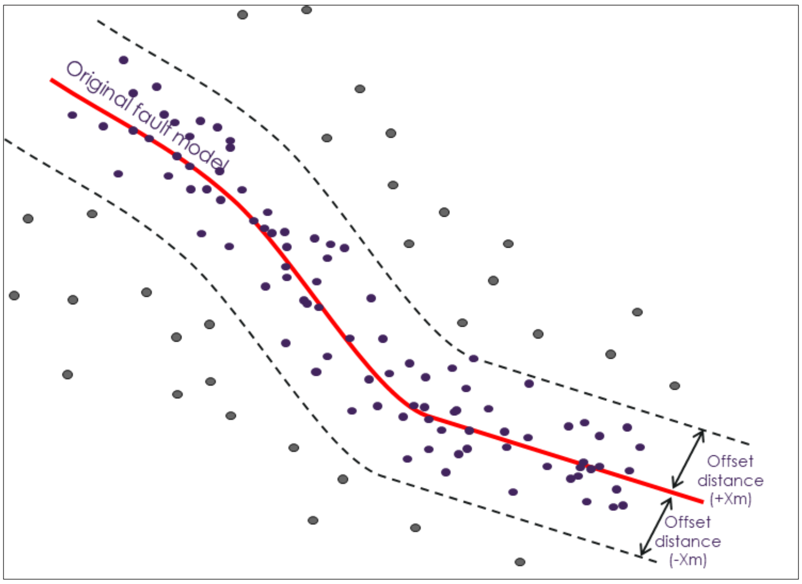

Figure 1. Domain setup for data selection

ANALYSIS METHOD

The following parameters were analysed to determine if the stages of failure could be identified within the mining data sets:

- Event rate
- Location
- Magnitude.

The weekly (7-day) trends of each parameter were anlaysed. The intention was not to standardize the results across each site, but to take real-world data with all its limitations and determine if precursory trends could be observed in the data. Event rate was assessed by calculating the average number of events per day for the previous 7 days on any given day.

Location was anlaysed using spatial correlation length (SCL) analysis which provides a numerical value for the proximity of events, relative to each other, for a group of events. Analysis is undertaken by firstly grouping an event with its nearest neighbour. This calculation is then repeated for a set number of events. For each pair, the distance between it and the next closest pair is calculated. The SCL is the average distance within the cluster. An SCL for each day was calculated for the events occurring within the preceding week. As the SCL analyses the inter-distance relationship between events the minimum number of data points for a given 7-day period was set as 5. This means that SCL was only calculated on days where 5 or more events occurred on that particular structure within the previous week. All events occurring within the 7 days were still used in the calculation.

The average magnitude (sum of magnitudes divided by the number of events) was calculated for each day for all events occurring in the previous 7 days. As the calculations determine averages, they are dependent on the number of events occurring per time period. The formula cannot be resolved where there is 1 event or less per day. In such cases, a value of 0 is applied.

Failure definition

Morton (2019) identified two types of failure that are critical to the stability of excavations within the mining environment. Instantaneous failures are described as significant seismic events typically causing damage to an excavation. These failures are defined using a critical magnitude the value of which is set by the mine site engineers. The results of the analysis of the trends in each parameter are provided in this paper; more than 300 instantaneous failures were analysed.

The second type of failure is called accelerating slip failure. This is defined as large increases in seismicity over short periods of time. This type of failure causes rapid degradation of the rock mass. Over time this can result in instability of the excavation resulting in loading of the ground support systems. Morton (2019) prescribed 20 events per day as failure to use in the analysis. Although this value was applied to all sites, in reality, the value should be determined as appropriate to the site conditions and the features being analysed. The results of the accelerating slip failures are not presented in this paper.

Conditional analysis

To determine if changes in parameters are occurring prior to failure, a conditional analysis method has been used. This analysis involves a simple yes / no test. The data prior to each instantaneous failure was collated and assessed to determine if the expected trend (increase or decrease) occurred. The assessment determined whether the expected trend was observed in the first day prior to rupture. More simply, the question posed was: was the value of the parameter higher (or lower) than the day of rupture. If the result of the assessment conforms with the expected trend, then the next day away from rupture is assessed (See Figure 2). This assessment was continued until a negative result was achieved or the limit of 10 days was reached. Whether the positive criterion is decreasing or increasing depends on the parameter being assessed. Event rate and magnitude are both expected to increase in the days prior to failure, whereas SCL is expected to decrease. All failures are assessed individually, and the number of successful outcomes is counted for each time period prior to the failure. The method of assessment of each parameter is described in the next section along with the results.

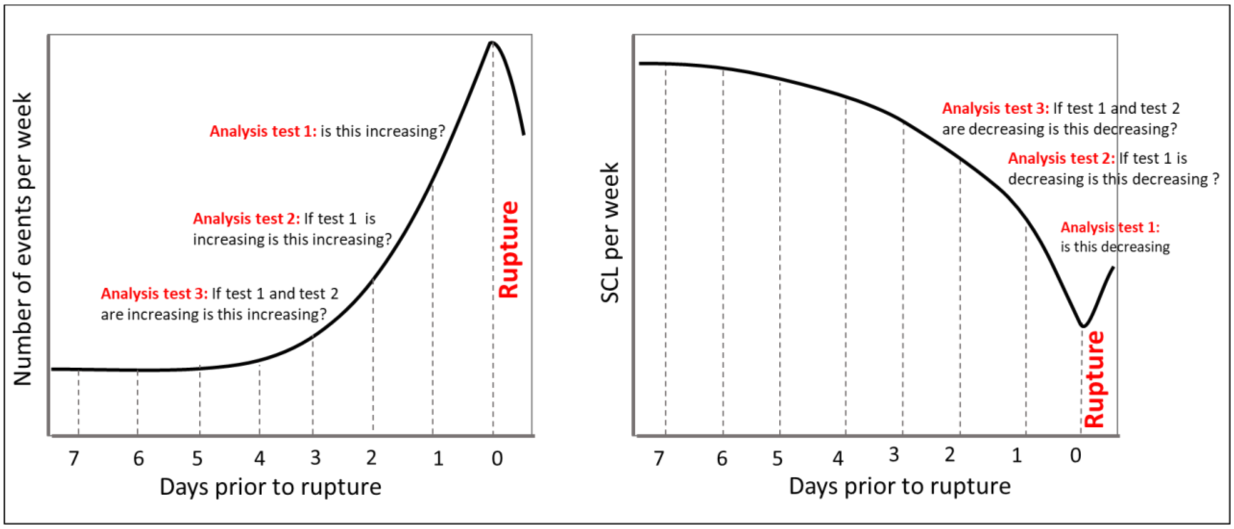

Figure 2. Example of conditional analysis for increasing and decreasing trends

EVENT RATE

Evaluation theory and method

The seismic event rate on each structure was assessed using the number of events per day. Theoretically, the event rate varies with the phase of failure. In the primary phase the event rate remains low but then begins to increase during the secondary phase with an exponential increase in the nucleation phase. This indicates that in the days prior to a rupture the event rate increases. Figure 3 provides the average number of events per 7-day chart. A qualitative assessment of the chart suggests that the characteristics of the stages of failure can be observed both on a macro full fault scale and a prior to smaller localised individual failures. To quantitatively determine how often an increase in event rate occurs before failure and how far from rupture the trends can be observed, each rupture on each structure was assessed. The statistical results are provided in Figure 4. The results demonstrate that between 10% and 20% of instantaneous ruptures occurring on structures indicate an increasing trend 7 days prior to rupture. On average, over 50% of instantaneous failures demonstrate an increasing trend for the 2 days prior to failure. However, depending on the nature of the structure this may range from 20% of failures to 60% of failures. This suggests that some structures will accumulate strain and fail suddenly, whereas some structures are likely to start to creep and then rapidly accelerate. This effect may be the result of the heterogeneity of the structure or the nature of mining along the structure. Over 80% of instantaneous ruptures demonstrated a lower 7 day rolling average event rate on the day prior to rupture compared with the day of rupture. This is logical as on the day of rupture there is frequently a large increase in events associated with the rupture itself.

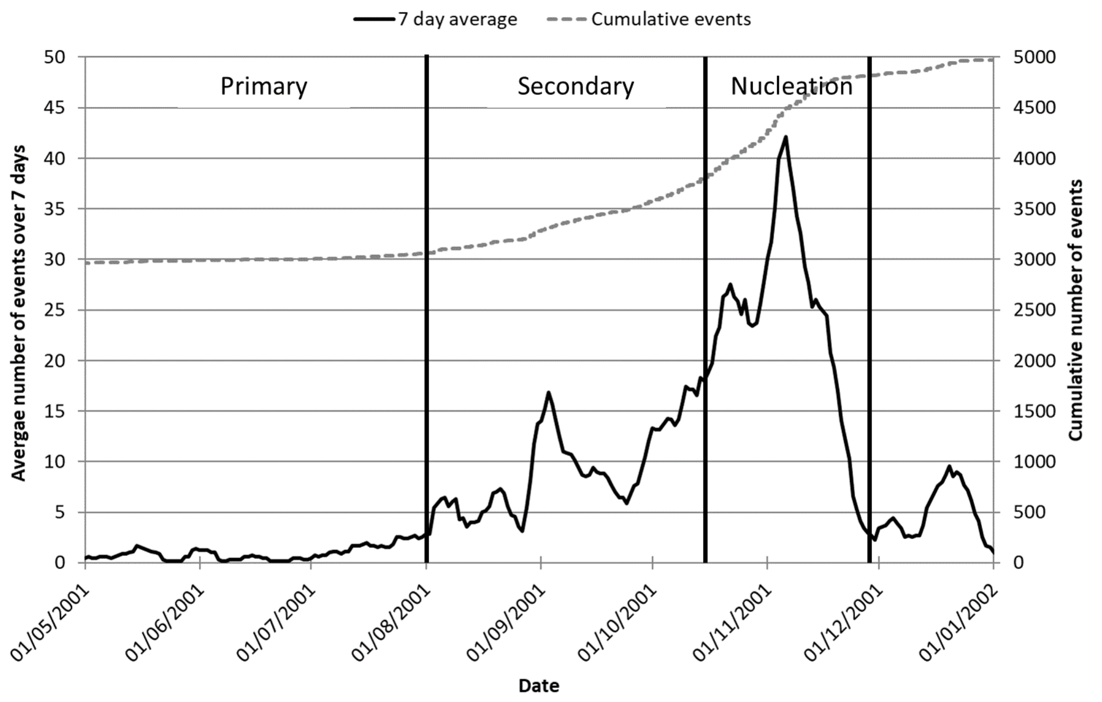

Figure 3. Stages of failure evident in the events per day and rolling 7-day average results

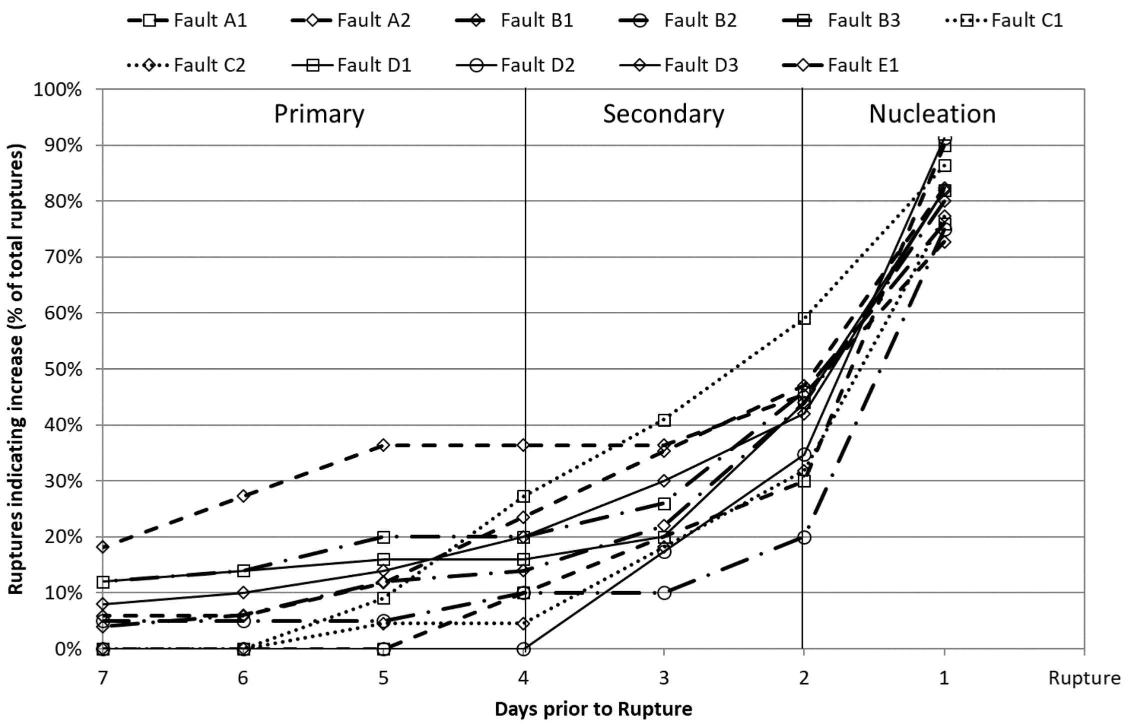

Figure 4. Results of conditional analysis of the trends in event rate prior to rupture

LOCATION

Evaluation theory and method

Acoustic emission studies have demonstrated that seismic events coalesce in the nucleation stage of failure. See Lockner et al (1991), Lei et al (2000). In the primary stages of failure, the events are randomly located throughout the sample. During the secondary stage of failure, the events begin to cluster. In the final nucleation stage, the events form a clear fracture plane just prior to failure. SCL was used to assess the coalescence of the seismic data. SCL is a measure of the distance between events. If the events are getting closer together, then the SCL will decrease. A minimum of 5 events were required for the calculation. Qualitatively, the SCL appears to be erratic in the primary stage. It becomes less erratic in the secondary stage. In all cases where the SCL drops below 10 it is accompanied by a significant increase in the event rate (Figure 5). Morton (2019) states that this was observed across all structures regardless of the site. The results of the conditional analysis are provided in Figure 6. The 7-day SCL results demonstrate that some ruptures indicate clustering up to 4 days prior to rupture. However, in total less than 50% of instantaneous failures show strong clustering the day prior to rupture. The results indicate that instantaneous failures are typically not associated with strong clustering days prior to an event.

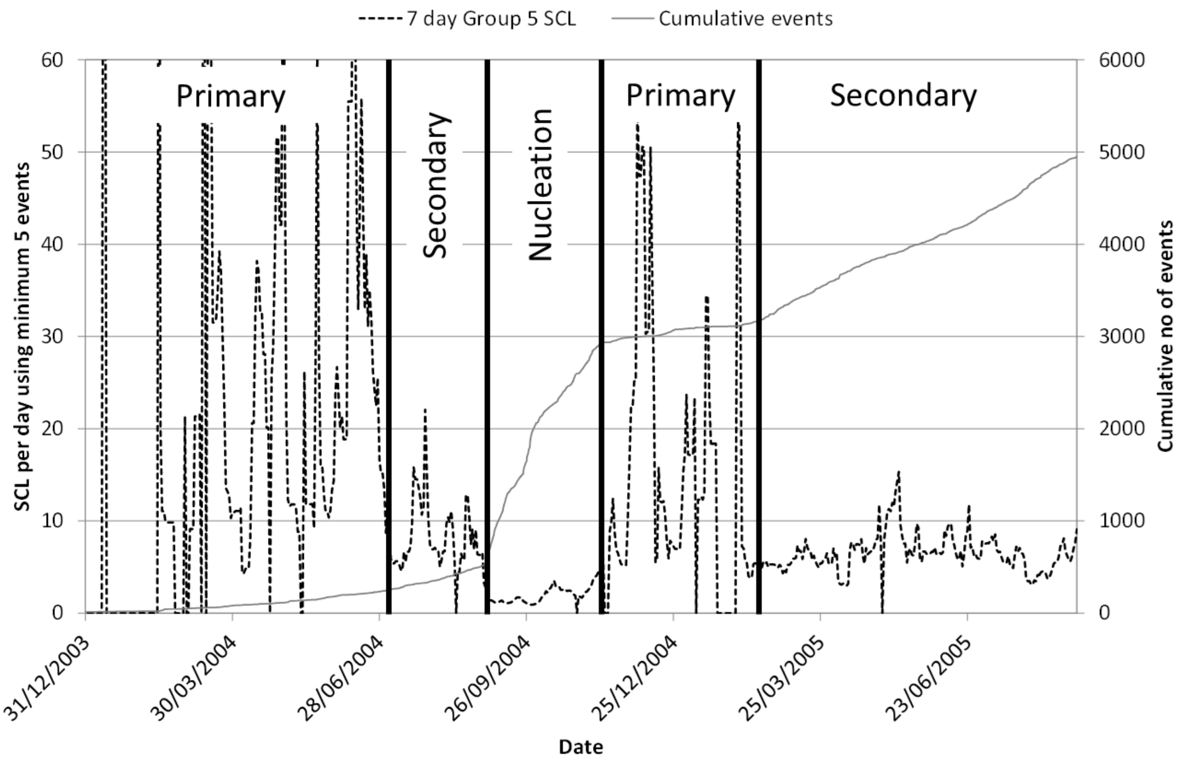

Figure 5. Example of the weekly SCL

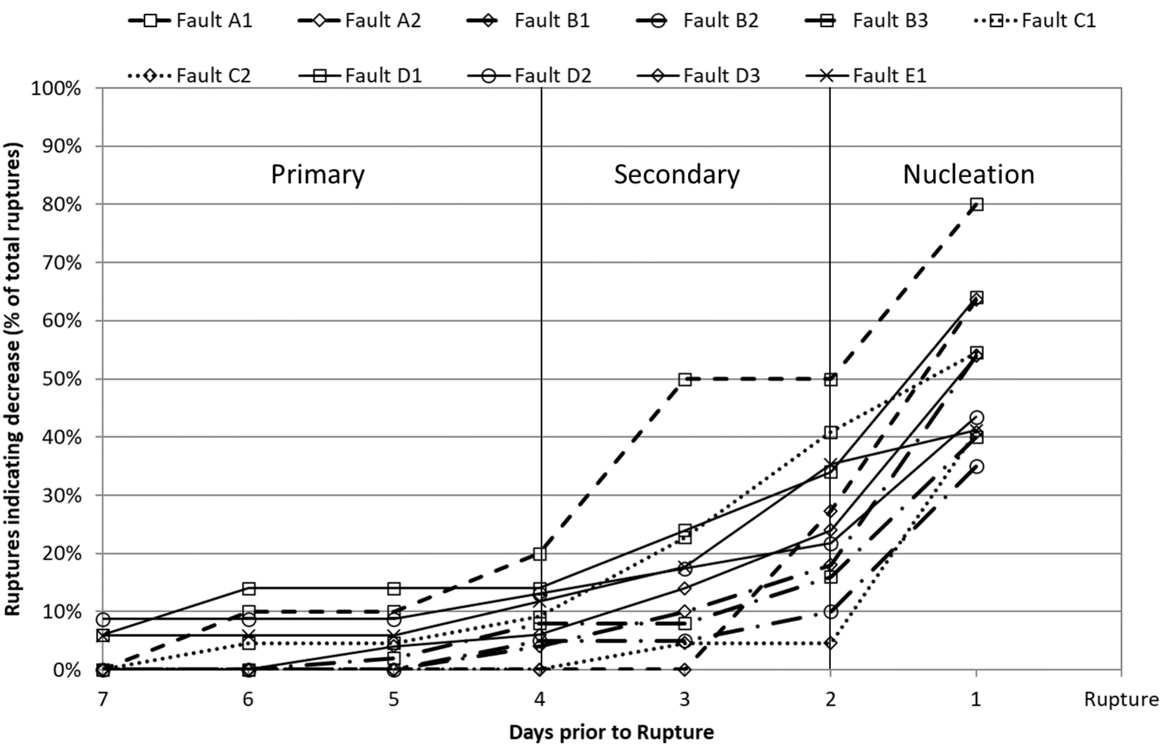

Figure 6. Results of conditional analysis of the trends in SCL prior to rupture

MAGNITUDE

Evaluation method

There are several methods for evaluating magnitude. In most circumstances, b-value is used for evaluation. The b-value is calculated by determining slope of the line formed by the Gutenberg - Richter relationship for calculating magnitude. Morton (2019) evaluated b-value data based on formula estimates proposal by Aki (1965). It was found that these formulae overcomplicated the analysis. It is much simpler to analyse the base value than to introduce additional estimates. Consequently, magnitude was evaluated as a stand-alone parameter. The calculation of magnitude was site specific. All sites except one used the same formula. No attempt was made to standardize this as the concept was to test real world data to determine if increasing magnitude trends could be identified prior to failure.

Theoretically, a major failure is preceded by a series of ruptures (foreshocks) that gradually increase in size and consequently magnitude. The time variations in magnitude was assessed to determine if increases could be identified prior to failure. An example of the results is provided in Figure 7. The results demonstrate that prior to failure, there is a short period of gentle increase in the average magnitude followed by a very rapid increase. Given how quickly these changes occur it suggests that the secondary stage is not as obvious in magnitude analyses as it is in the other analyses described above.

The results of the conditional analysis are provided in Figure 8. The results demonstrate that there are few indications of failure beyond 5 days prior to rupture. Less than 20% of failures have a continually increasing magnitude trend 3 days prior to rupture. Over 70 of instantaneous failures have a lower 7-day average magnitude compared with the day of rupture. This is logical as the definition of instantaneous failure is based on magnitude and hence the magnitude on the day of failure will be inherently high. In the cases where the magnitude does not increase on the day of failure compared with the day before failure, it is likely that strong aftershocks from the main failure have occurred.

These aftershocks still conform with the magnitude criterion that has been used in the definition of instantaneous failure as described above.

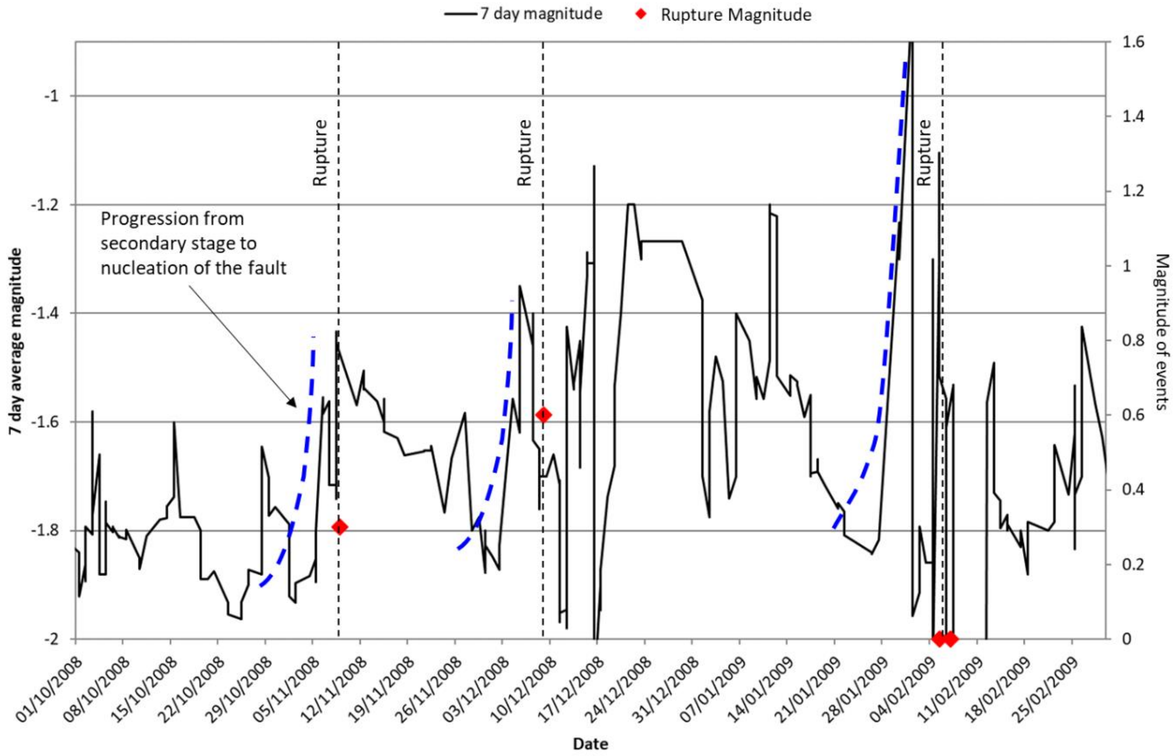

Figure 7. Example of time variations in the 7-day average magnitude

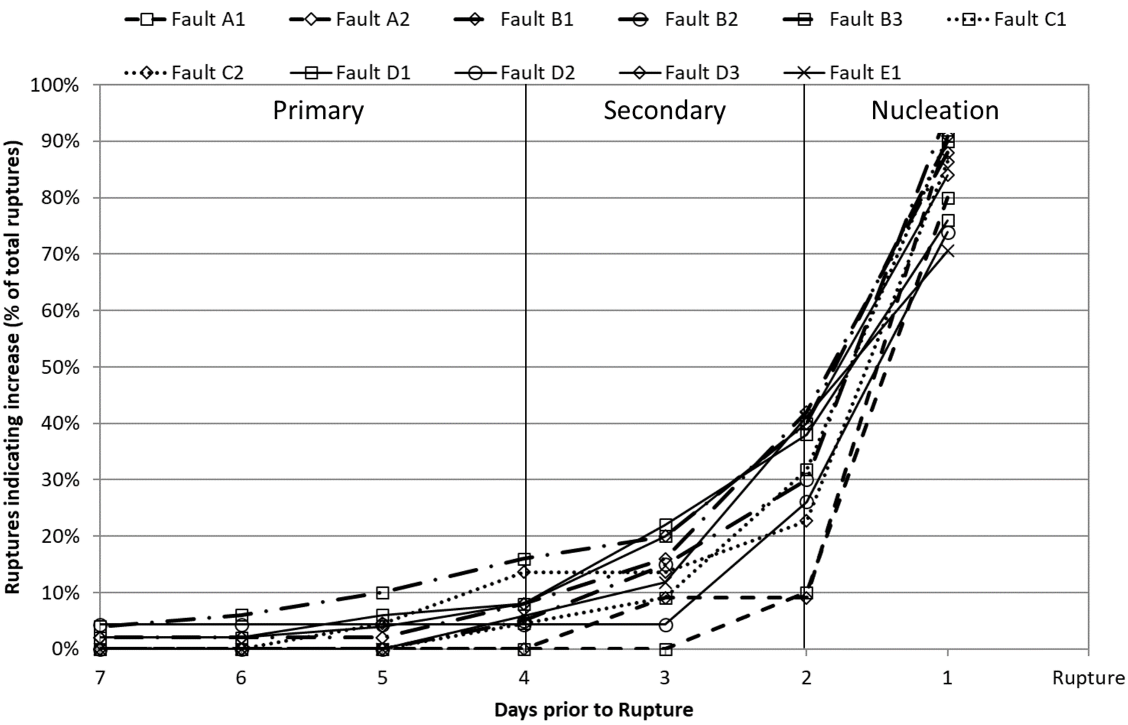

Figure 8. Results of conditional analysis of the trends in magnitude prior to rupture

COMPARISON OF PARAMETERS

To determine the most useful parameters for analysis, a comparison of the results was undertaken. The results for the instantaneous failures are provided in Figure 9. They demonstrate that failure cannot be conclusively discerned 5 days prior to rupture. All parameters for both failure modes show increasing indications of failure 3 days prior to rupture with obvious signs in the day prior to rupture. Event rate and magnitude are similarly useful in demonstrating potential approaching failure, with approximately 20% of failures indicating positive trends (increasing or decreasing depending on the parameter) 3 days prior to rupture. SCL was the least useful parameter for examining instantaneous failures suggesting that clustering prior to large events provides limited information.

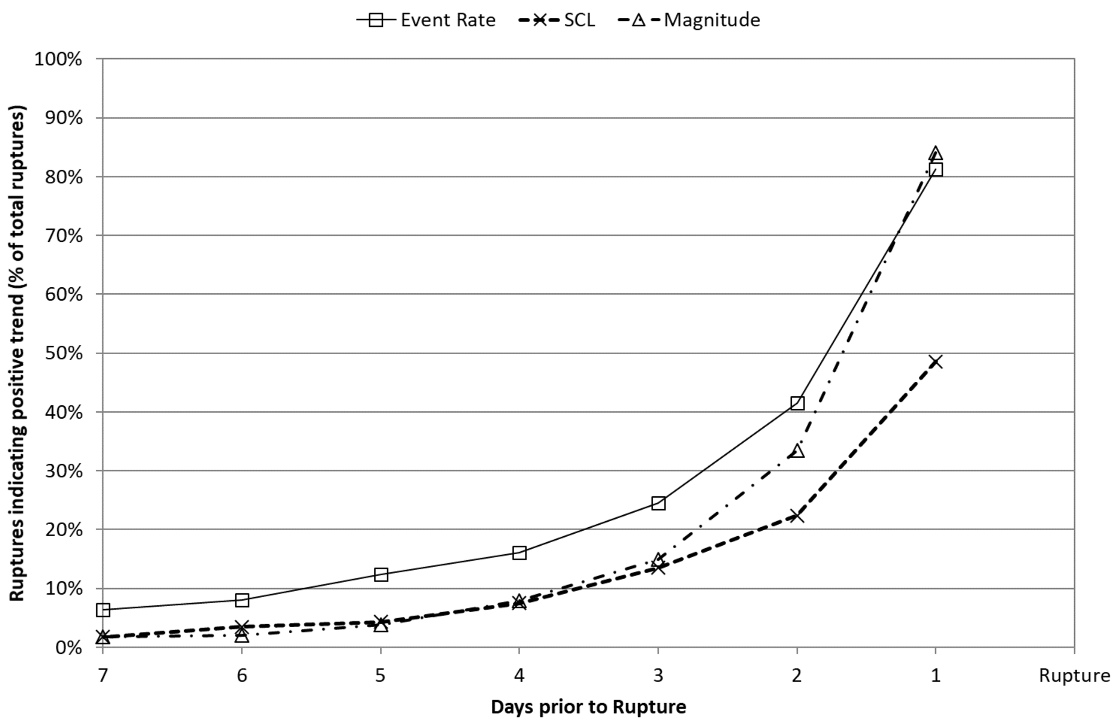

Figure 9. Comparison of the conditional analysis for each of the parameters

FORWARD ANALYSIS AND EVENT OCCURRENCES

The summary of results presented within this paper rely on the back analysis of failures to determine the rate of occurrence of specific trends. The results indicate that transition from the primary to secondary stage of failure occurs between 3-4 days prior to an event. To determine if this knowledge can be used in forward analysis, the number of occurrences of 3 consecutive days of increases or decreases in each parameter were determined.

The results indicated that for all parameters, less than 10% of monitoring days have 2- 3 prior days where the trends are consistent with the required trend for failure (increasing or decreasing). In terms of an annual rate this suggests that less than 30 days a year will have trends that may indicate approaching failure. These results suggest that it would not be onerous for sites to analyse changes in parameters such as event rate and event locations on a regular basis. When 3 consecutive days of increase or decrease in a parameter occurs the cause of such trends should be investigated.

DISCUSSION AND CONCLUSION

Overall, these results have demonstrated that the phases of failure can be observed in mining seismic data. Quantitative analysis has shown that individual parameters are able to provide indications of failure up to 3 days prior to the rupture. It is unlikely that impending failure can be determined earlier than 5 days prior to rupture regardless of the failure mode. The most universally useful parameter for analysis of the progression of failures is event rate with other parameters providing supporting evidence.

Given that these patterns can be identified in the mining data it suggests that seismicity is self-similar and fracturing patterns are the same at all scales. This means that studies conducted at small scales can be used to derive behaviours at larger scales.

Timeframes for analysing mining seismic data are often long. Few sites undertake analysis of seismicity trends in less than daily increments. These timeframes may not be adequate to enable the assessment of the temporal changes in seismic data. Analysing parameters in real time in conjunction with each other will provide useful data for Mine Site Engineers in the assessment of seismic hazards within the mining environment.

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Ellen has spent 20 years in the mining industry as a geotechnical engineer. Her main areas of expertise include geotechnical engineering in high-stress environments, seismic hazard management and the development of systems, and ground-support design for both static and dynamic conditions.

Ellen's expertise also extends to open-pit geotechnical studies involving site investigations, geotechnical core logging and mapping, rockmass characterization studies, and slope-stability analysis.

Ellen joined AMC in November 2017 as a principal geotechnical engineer. Since then, she has undertaken assessments in narrow-vein underground mines in Scandinavia, open-pit and underground investigations in Russia, and conducted a geotechnical audit of underground operations in Canada.

Prior to this, Ellen spent time as a geotechnical engineer at Spotted Quoll Nickel Mine, Black Swan Nickel Mine and Kundana Gold Mine, all within the Western Australian Goldfields region. These mines were all narrow-vein open-stoping operations with significant structural offsets that affected the behaviour of the rockmass. These roles involved the development of systems and processes for the management of geotechnical issues on each site. These issues included seismicity, yielding and dynamic ground support designs, rockmass studies, and the development of structural geology models for geotechnical assessments.

Additional to practical experience, Ellen has also undertaken industry-based research into the static behaviour of surface support elements and the seismic behaviour of large-scale structures. She has completed her Masters degree by research entitled "The static behaviour of large-scale ground support panels". The research involved the construction of the facility along with the development and analysis of test results.

Ellen has recently completed a Doctorate of Philosophy (PhD) thesis entitled "Seismic response of large-scale structures" which involved the analysis of real-life mining data to determine if precursory trends in data could be identified prior to failure.