

Validating a support performance database based on passive monitoring data

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Abstract

This paper reports on an on-going analysis of support performance at Vale's Creighton Mine covering the period from January 2000 to September 2011. A database was constructed of 133 rockbursts and the associated damage to support systems at 191 locations. The main source of information has been obtained through the seismic systems and on-site assessments. This work validates the information collected on site in order to quantify the performance of different support systems in a seismically active mine.

1 Introduction

Mining at depth faces a series of major technological challenges to ensure safe and profitable exploitation. A major challenge is the increase in stresses associated with greater depth and the potential for rockbursts, i.e. damage to excavations that occur in a sudden or violent manner and is triggered by a seismic event. Rockbursts can compromise production goals and endanger the safety of the workforce and mining equipment. Consequently, the selection of appropriate support systems capable of mitigating rockburst-induced damage is of great importance to an operation.

Over time, several guidelines have been developed, based on reasonable hypotheses, in order to assist in the selection of support systems able to mitigate damage. Nevertheless, these guidelines do not appear to be validated with quantifiable data. Recent efforts to provide further information through large scale dynamic test rigs and simulated rockbursts provide useful results but are difficult to interpret and extrapolate to field conditions (Hadjigeorgiou and Potvin, 2007). In order to develop guidelines to design support systems capable of withstanding dynamic loads, it is essential to assess the in situ performance of support systems.

Morissette et al. (2011) reported on data collection and statistical analysis, aiming to develop such guidelines. This paper summarises the steps taken into reviewing and validating the developed database. This involved adding more recent events including newer support systems, investigating new variables, and challenging the assumptions in Morissette et al. (2011). This critical assessment resulted in modifying the original assumptions that could not be defended with a high degree of confidence. This involved a change in strategy on the way data were treated in order to arrive at practical recommendations. This paper presents the validated database at Creighton Mine from January 2000 to September 2011.

2 Data collection

For the purpose of this investigation, it was decided to focus on data from one mine site. Creighton Mine of Vale was selected due to its long history of mining, seismicity and rockburst, the quality of its seismic data, and the considerably large range of event magnitudes recorded. The mine has always had a dedicated ground control team. A variety of rock support systems have been tested at Creighton during the past, making this mine site even more interesting for passive monitoring of support performance. This section provides the necessary background on the local geology at Creighton, mining methods and ground support practices. Sources of information available on-site and data collected are further reviewed.

2.1 Local geology and mining methods at Creighton Mine

Creighton Mine is located 20 km west of Sudbury, in Ontario, Canada. The mine, in production since 1901, currently operates at a depth of 2,420 m and its current extraction rate is approaching 3,400 metric tonnes per day. High magnitude seismic events are a regular occurrence at Creighton due to the mine depth and the presence of major seismically-active structures.

The mine is characterised by a granite-gabbro footwall and a norite hangingwall. Most of the ore is located at the FW-HW contact but massive sulphide lenses are also located in shear zones, extending several hundred meters into the footwall (Cochrane, 1991). Part of the mineralisation in the upper mine is also comprised of disseminated sulphide in sub-layer norite. Most reserves and resources are concentrated in the Deep 400, 461, and 649 orebodies, Figure 1.

At Creighton Mine, it is recognised that the geomechanical zones correlate well with the various geological zones. Nevertheless, a late-stage set of faults and fractures, referred to as shear zones, are associated with poor ground conditions and exhibit a low level of microseismic activity. These structures consist of several individual fractures developed in an en-echelon pattern that can vary in thickness from a few centimetres to tens of meters (Malek et al., 2008). Both the geological zones where rockbursts are located and the presence of shear zones have been accounted for in this investigation.

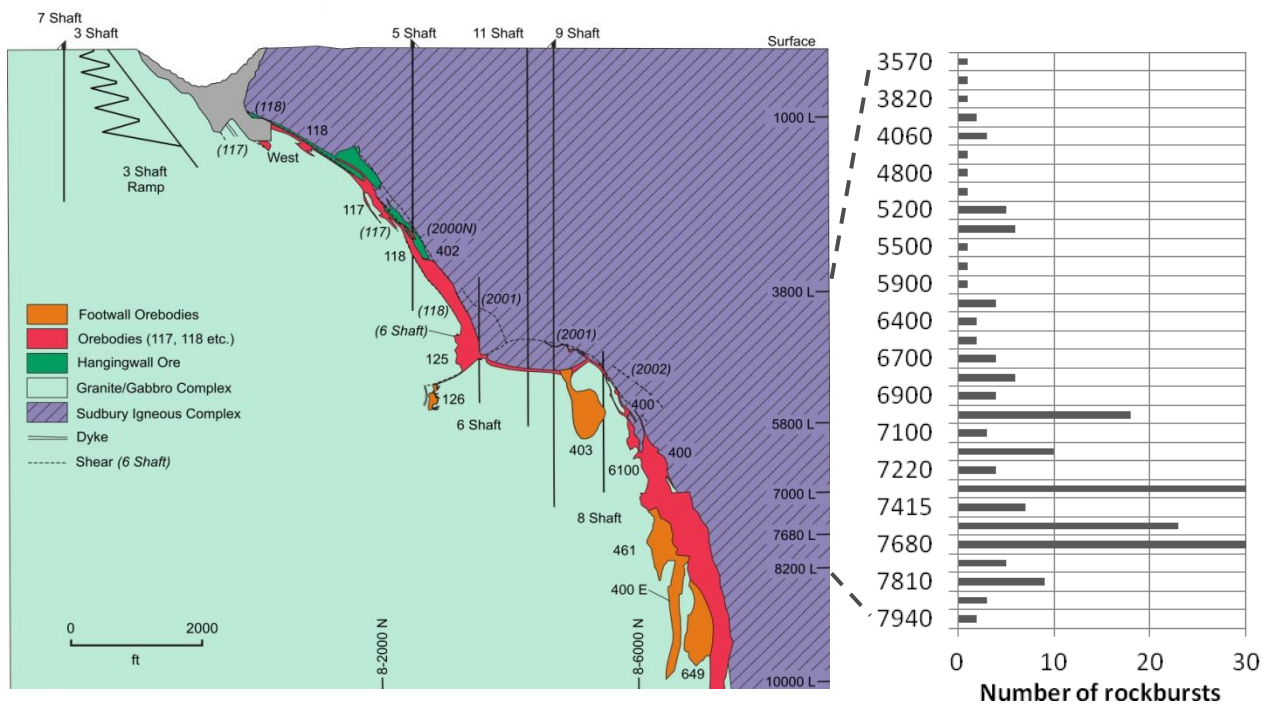


Figure 1 Composite geology section of Creighton Mine, looking West (Vale Inco, 2009), and number of damage locations resulting from rockbursts between January 2000 and September 2011

As it is expected from a mine in production for more than 100 years, several mining methods were used at Creighton. In the upper area, blastholes, cut-and-fill, and vertical retreat mining have been used. Today's most economically important area of the mine is located below the 6400 level (1,950 m) and is known as Creighton Deep. The ore located in this area is extracted with a pillarless slot-and-slash method and a top-down centre-out sequence. This method was selected in order to deal with higher levels of stress and a greater rate of mine-induced seismic events.

The evolution of mining methods shows that these were adapted to the various conditions encountered underground. However, despite the selection of what appears to be an appropriate mining method for Creighton Deep, rockbursts are still a regular occurrence. As demonstrated in Figure 1, more than 85% of all

rockbursts that occurred between January 2000 and September 2011 were located below the 6400 level. Consequently, the evolution of support systems in this area is of critical importance.

2.2 Support standards at Creighton Deep

Ground support for Creighton Deep has been modified over time based on field trials and analyses (Malek et al., 2008). As of November 2006, the minimum rock support system consisted of an alternate pattern of 2.4 m long resin rebars and mechanical bolts at the back and 2.0 m long 46 mm friction sets at the walls. Reinforcement was installed on a 1.2 x 1.5 m staggered pattern, overlapping No. 4 gauge galvanised welded wire-mesh down to the floor. Shotcrete was also used as surface support in addition to the screen. In burst-prone conditions the support standard was enhanced by the addition of 2.4 m long modified cone bolts and No. 0 gauge straps or shotcrete arches (Malek et al., 2008).

The minimum support system was further modified in June 2010 by replacing the reinforcement pattern of alternating rebars and mechanical bolts, by eliminating mechanical bolts at the back and replacing them with rebars. This action was taken in response to frequent failures of mechanical bolts under dynamic loads. The June 2010 standard was further modified in September 2010 for level 7810 and below. The reinforcement at the back currently comprises of a 1.2 x 1.0 m staggered pattern of resin rebars and modified cone bolts. Primary reinforcement at both the back and the walls is installed with No. 0 gauge wire-mesh square straps (0.3 m) over-lapping No. 4 gauge screen. In critical areas, the support system is enhanced by installing modified cone bolts and No. 0 gauge straps at the wall. Shotcrete is no longer part of the minimum support standard, as it was observed that it could not manage some of the loads.

2.3 Main sources of information

A comprehensive data collection campaign was undertaken on site. The majority of seismic and support data were collected between May and August 2010. Available data were validated by cross-referencing and a site specific retrievable database was constructed. The database was further complemented with data collected in September 2011. In total, 133 series of rockbursts that occurred at Creighton Mine between January 2000 and September 2011 were investigated. These events resulted in damage to 191 specific locations. Figure 2 is a common example of rockburst-induced damage at Creighton Mine.



Figure 2 Approximately 4 tonnes of material were displaced at the back of the 7400 powder magazine on 18 May 2011, following CR1418 rockburst

2.3.1 Description of rockburst occurrence and support damage

A valuable source of information for this study was the ‘Unusual Occurrence Reports for Groundfall/Rockburst’ prepared by the mine personnel for the Mines and Aggregates Safety and Health Association of Ontario (MASHA). These reports identified the areas affected by the rockburst and provided a qualitative assessment of the performance of each reinforcement and surface support element. In reviewing the history of events over 10 years, it was recognised that a shortcoming of the report format was that it is best suited for recording events that result in only one damage location. Inconsistencies in the reports and variations in the accuracy of information were also observed due to different interpretations among ground control personnel. Therefore, during the field data collection process, the information was complemented by on site interviews of mine personnel and cross referenced with site inspections, technical reports, and CAD layouts.

2.3.2 Seismic events location and magnitude estimates

The microseismic monitoring system at Creighton Mine was used to extract the 3D coordinates of the seismic sources. Available sources of information for extracting event magnitudes consisted in the local macroseismic system and reports provided by the Geological Survey of Canada (GSC). Magnitudes were calculated on site by a Hyperion Digital Drum Recorder (HDDR) system until May 2008 when it was replaced by a 24-bit Paladin macroseismic system. Both were calibrated to correlate to the recorded magnitude levels reported by the GSC.

The quality of seismic data was reviewed in order to ensure that the change in the macroseismic system did not introduce a discrepancy in the magnitude dataset. As both the HDDR and the Paladin systems were calibrated to the GSC, it was possible to assess the quality of their estimates by comparing magnitudes that were captured by both the local macroseismic system and the GSC. Figure 3 illustrates this comparison as each point corresponds to the over or underestimation of the magnitude calculated by the local macroseismic systems with respect to the GSC magnitude. The magnitudes estimated by the Paladin system are represented in red while those estimated by the HDDR system are represented in blue. The HDDR population is clearly bimodal with distinct trends developed at GSC 2.5 magnitude. Consequently, these populations were analysed separately.

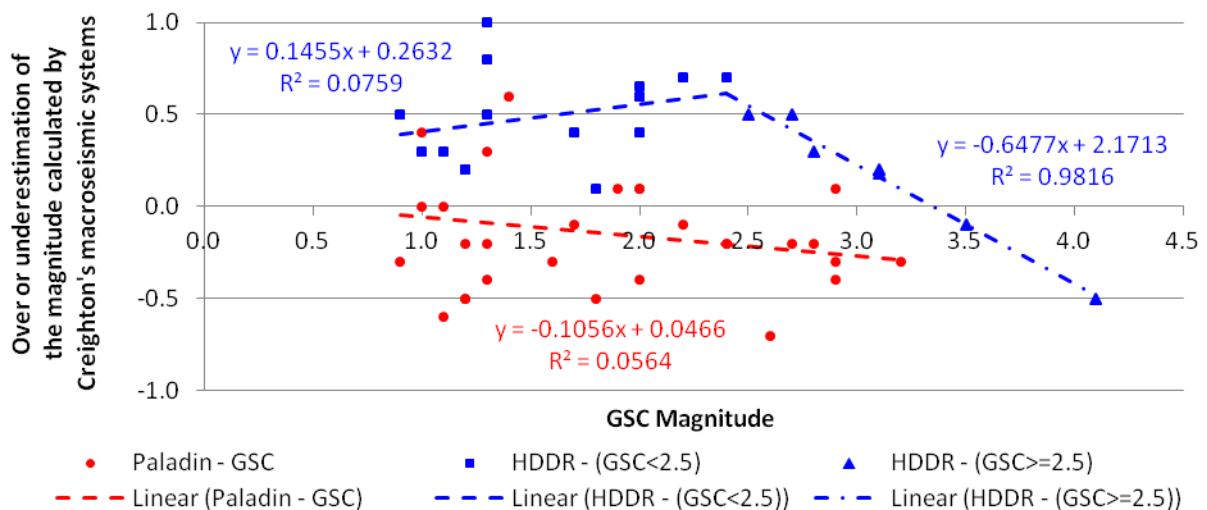


Figure 3 Magnitude over or underestimates produced by the macroseismic systems employed at Creighton Mine with respect to the GSC Magnitude

A student test of hypothesis on samples mean was used to determine if a given seismic system significantly overestimated or underestimated the magnitudes with respect to the GSC. This analysis demonstrated that the Paladin system tended to underestimate magnitudes by 0.2 Nuttli while the HDDR system tended to overestimate magnitudes by 0.5 Nuttli when the magnitude was smaller than GSC 2.5. Therefore, it was

decided to increase the magnitudes calculated by the Paladin system by 0.2 and to decrease the HDDR magnitudes smaller than 3.0 Nuttli by 0.5.

Magnitudes calculated by the HDDR system that were greater than GSC 2.5 were excluded from this analysis as they were not characterised by a normal distribution around the mean. A least-square regression model was applied and further validated with the analysis of variance (ANOVA). The following adjustment was proposed for HDDR magnitudes greater than 3.0 Nuttli:

$$(\text{Magnitude} - 2.17) / 0.35 \quad (1)$$

2.3.3 Mining-induced stress

In situ stress conditions at the damage location were quantified using the deviatoric stress. This parameter was obtained from numerical modelling results with FLAC3D, a three-dimensional finite difference model (Itasca, 2009). This report provided a forecast of long term mine-induced stress conditions based on the proposed life-of-mine sequence for Creighton. It was of particular interest as it reported the results from the numerical model calibration with respect to observed mine induced seismicity from 2003, and from 2005 to 2009 for levels 7400, 7530, 7680 and 7810. This information was used to estimate the stress conditions at 45% of the analysed rockburst damage locations. The reported deviatoric stress was normalised to the unconfined compressive strength specific to the geomechanical zones where damage was observed. This was the first step in this project where the stresses were analysed with respect to the resulting damage at a mine wide level. It was observed that there was a clear correlation between the induced stresses and the geomechanical zones. This is addressed further in Section 3.2.

2.4 Data reduction

A filter was applied to the database in order to focus on access galleries developed in rock. Damage to vertical excavations and development located in backfill were not considered as they were out of the scope of this project. Rock support systems reported at damage locations were also considered in the data reduction process. Further data reduction was undertaken by limiting the statistical analyses to support systems present in at least three locations subjected to rockburst. Finally, rockbursts reported in the database had to be characterised by a seismic event magnitude and a set of 3D coordinates in order to be considered. Observations that presented missing data for the seismic event magnitude and/or seismic event location were filtered out. Following data reduction, 122 rockburst damage locations remained in the database.

The collected variables were organised based on whether they were of quantitative or qualitative nature. A first set of variables was analysed with principal component analysis (PCA). This PCA led to the identification of superfluous qualitative variables that resulted in increasing the variability of the statistical model (Morissette et al., 2011). Further data reduction was conducted in order to remove these variables. Table 1 summarises the variables that were used for further statistical analysis.

Table 1 Variables retained for the statistical analysis of rockburst data

Quantitative Variables	Qualitative Variables
Adjusted Nuttli magnitude of seismic events	Damage to single or multiple locations (S, M)
Distance between seismic source and damage (m)	Seismic source mechanism (fault slip, strainburst)
Hydraulic radius of the cross section of openings (m)	Geological zone where the seismic source is located (hangingwall, footwall, ore)
$(\sigma_1 - \sigma_3) / \text{UCS}$ at the damage locations	Geological zone where the damage is located (hangingwall, footwall, ore)
Tonnage displaced at the damage locations	Shear zones in the vicinity of damage (yes, no)

2.5 Identification of support systems

The present investigation covered an eleven-year period. Consequently, the collected data include a range of systems, some of which may have been since abandoned. For example, data from support systems installed on the wall contain variations of friction sets and No. 4 or No. 6 gauge wire-mesh often complemented with shotcrete. Furthermore, although this study focused on events that occurred between January 2000 and September 2011, it followed that some of the areas affected were developed prior to 2000. This explains that 72 support systems were identified as being installed in areas hit by rockbursts.

The identification of support systems at collected rockburst locations was based on the type of reinforcement and surface support elements installed and did not differentiate small variations in bolt length and installation patterns. In total, 34 distinct support systems were used to support excavations back and 38 for supporting the walls. Data reduction was conducted as stated in the previous section, resulting in the use of 13 support systems at the backs and 16 at the walls. This reflects that the mine has used different combinations of reinforcement elements at the back and a range of friction bolts at the walls. Each support system was assigned an identification number, starting by 1 if installed at the back or 2 if installed at the walls.

Table 2 summarises the employed support systems that were exposed to rockbursts at more than five locations and provides a breakdown of the individual elements. These support systems are consistent with the ground support standards used by the mine. Even if eleven years of rockburst data were analysed, only 11 support systems out of the 29 comprised more than 5 observations. This result highlights the challenge of determining the capacity of support systems in a statistically significant manner, given the evolution of support strategy at any mine site.

Table 2 Identification of rock support systems following data reduction (extract from the constructed database)

Support Systems		101	102	104	105	107	108	204	210	211	213	214
Reinforcement	Mechanical bolts	X	X	X	X	X	X					
	Rebar		X	X	X	X	X					
	FS-35							X				
	FS-39								X	X		
	FS-46										X	X
	Cable bolt					X						
	Modified cone bolt							X				
Surface Support	No. 6 welded wire-mesh		X									
	No. 4 welded wire-mesh	X		X	X	X	X	X	X	X	X	X
	Shotcrete				X	X	X			X		X
	No. 0 straps						X					
Number of rockbursts		7	5	38	37	14	6	13	27	38	12	5

3 Statistical analysis of rockburst data

Traditionally, there is a perception that certain support systems perform better or worse when subjected to seismic loads. This is, however, often difficult to quantify. The data collected at Creighton Mine presented an opportunity to further investigate the validity of such perceptions. It is opportune to consider whether

the available quantitative and qualitative data can provide reliable results that can facilitate the interpretation of seismic loads on different support systems.

3.1 Revision of the methodology

A first statistical analysis was conducted with the PCA technique by Morissette et al. (2011). This analysis was based on the assumption that the performance of support systems could be assessed by considering the tonnage displaced during rockbursts. In cases when damage was reported at more than one surface, e.g. back and wall, it was assumed that the same proportion of material was displaced from each surface.

Meanwhile, a review of the qualitative performance of individual support elements demonstrated that these assumptions could not be supported with a high level of confidence. Based on the reported qualitative observations, there was no clear correlation between the damage of the reinforcement and support elements and the displaced rock mass (tonnage). Also, when the material was displaced from more than one surface, the support installed at those surfaces rarely sustained the same level of damage. Therefore, it was not justified to simply divide the displaced tonnage by the number of damaged surfaces. Figure 4 represents the number of surfaces or combination of surfaces damaged by rockburst, following data reduction. As damage to back and wall is the largest category after damage to the wall, it is justified to revise the approach.

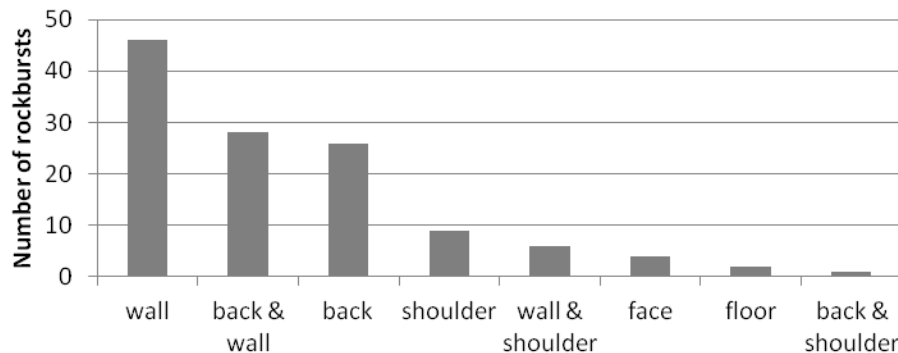


Figure 4 Number of rockburst that induced damage to each surface or combination of surfaces

It is recognised that the capacity of support systems will have to be assessed based on qualitative observations. The tonnage displaced during rockbursts is not retained any longer as an index of support capacity. This parameter has to be considered, however, in order to assess the demand on support systems during a rockburst. PCA is conducted on the updated dataset in order to identify correlations among variables that can impact the demand. Variables that present a greater level of correlation are further analysed.

3.2 Interpretation of PCA results

A PCA model was created with Simca-P+ (Umetrics, 2009) based on the variables listed in Table 1. The PCA model was fit by two components and was characterised by a degree of fit (R^2) of 0.507 and a predictive ability (Q^2) of 0.055. The fit explains the capacity to mathematically reproduce the dataset and is measured by R^2 , the 'goodness of the fit' (Eriksson et al., 2006). In the case of a dataset that is perfectly fit by a statistical model of increased complexity, R^2 reaches its maximal value of 1. The opposite, i.e. a dataset that is poorly fit by a model, is characterised by a R^2 value approaching 0. The R^2 of 0.507 calculated for this PCA model seems acceptable considering that the problem dealt with more qualitative variables than quantitative variables.

The predictive ability of a statistical model refers to its capacity to accurately predict variables, either internally via existing data or externally through the use of an independent set of observations (Eriksson et al., 2006). Simca-P+ uses cross validation to estimate the predictive ability of a model via the parameter Q^2 , the 'goodness of prediction' (Eriksson et al., 2006). Q^2 is less inflationary than R^2 ; hence it does not tend to

reach its theoretical maximum value of 1 with increasing model complexity. The Q^2 of 0.055 is relatively low and consequently demonstrates that a predictive model could not be established based on the Creighton’s dataset. Nevertheless, given that most of the variables are qualitative and appear to be fairly independent of each other, the resulting Q^2 value is arguably satisfactory.

The objective in the PCA undertaken was to recognise patterns in the data by identifying correlations among variables. Projections on a plane composed of the principal components 1 (PC1) and 2 (PC2) were analysed. The loading scatter plot presented on Figure 5 represents the parameters that multiply each variable for PC1 on the X-axis and PC2 on the Y-axis. These parameters are called loadings.

On the loading plot, variables close to each other are positively correlated whereas those opposite to each other are negatively correlated. For example, PC1 demonstrates that rockbursts that occur in the hangingwall are positively correlated with seismic source located in the hangingwall, fault slip mechanism, greater event magnitude, and greater distance between the seismic source and the damage. These events usually result in multiple damage locations. On the other hand, these variables appear to be negatively correlated with strainburst events that occur in the footwall, which usually result in a single damage location. These observations are consistent with the theory as it is recognised that self-initiated rockbursts (e.g. strainbursts) are very local in nature and generate damage in a specific area. On the other hand, rockbursts triggered by remote relatively large magnitude seismic events (e.g. fault slips) have the potential to generate damage in many areas (Kaiser et al., 1996).

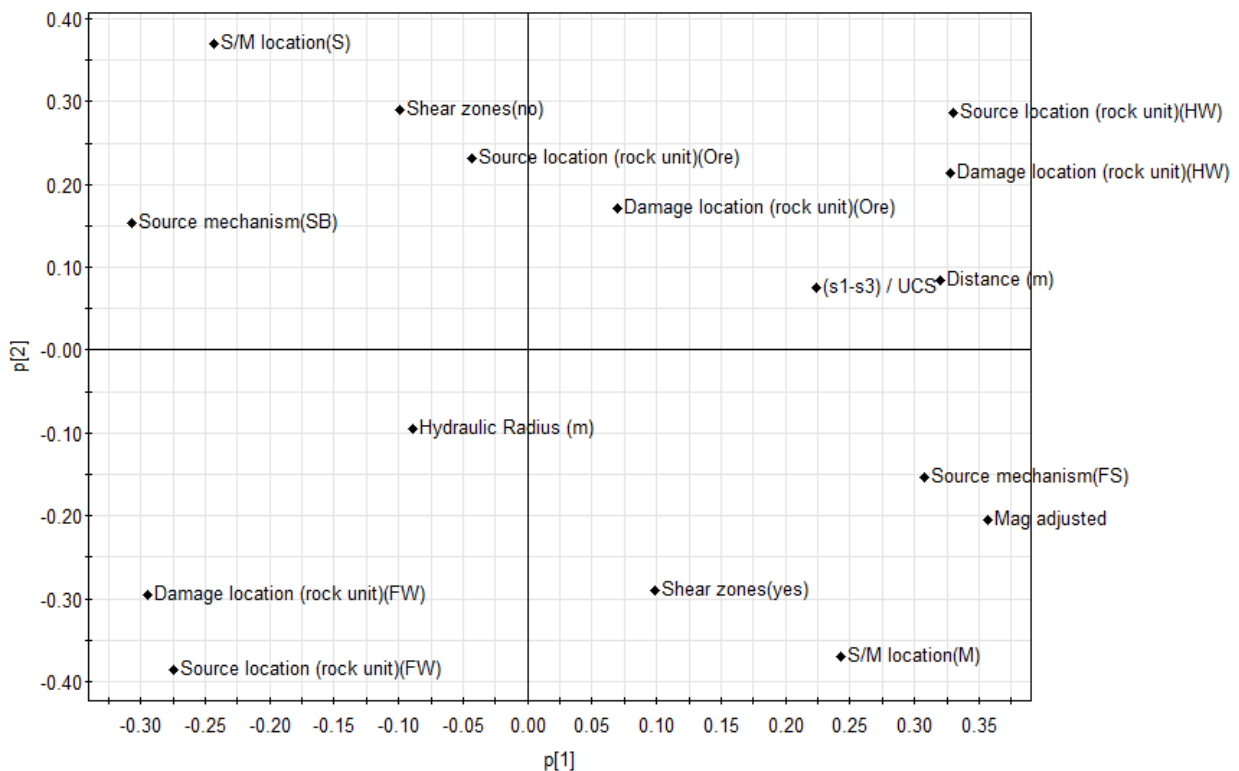


Figure 5 Loading scatter plot of the PCA model

The loading plot in Figure 5 demonstrates that the seismic event magnitude and the distance between seismic source and damage are the most significant quantitative variables in PC1 with a loading of 0.36 and 0.32, respectively. The level of stress as represented by $(\sigma_1 - \sigma_3) / UCS$ also has a considerable impact with a loading of 0.22 in PC1. The position of $(\sigma_1 - \sigma_3) / UCS$ on the loading plot also demonstrates that excavations located in the hangingwall and those located in the ore usually encounter higher levels of stress. This is intuitively correct as these excavations are located closer to the mined-out areas, where stress concentrations occur.

The variation induced by shear zones is mainly captured by PC2. It is observed that the presence of a shear zone in the vicinity of damage is positively correlated with rockbursts that occurred in the footwall. It also appears to be positively correlated with fault slip events of larger magnitude and multiple damage locations, in PC2.

The cross section area of an excavation, as defined by its hydraulic radius, was used to compare openings of different size. The hydraulic radius appeared to have only limited correlation with other variables. Nevertheless, there was a positive correlation between the hydraulic radius and the occurrence of rockburst in the footwall. This demonstrated that excavations characterised by a larger cross section were generally located in the footwall.

The relative position of variables on the loading scatter plot is relevant in order to classify rockbursts based on data similitude. It is observed that rockbursts can be classified according to the geospatial distribution of damage and the characterisation of the seismic source. These categories are subdivided in Table 3. The difference between the number of damage locations in the ore and the number of strainbursts located in the ore or hangingwall demonstrates that a considerable proportion of damage in the ore body is associated with seismic events that are located in different geological zones. Ten seismic events were not assigned a seismic source mechanism by the mine personnel. It is possible, however, to assign a seismic source mechanism retroactively based on the interpretation of the PCA.

Table 3 Sub-categories of rockburst established based on data similitude. The number of rockburst counted into each sub-category is indicated in brackets

Geospatial Distribution of Damage	Seismic Source Characterisation
Hangingwall (15)	Fault slips located in the hangingwall (15)
Footwall with shear(s) (29)	Fault slips located in the footwall (27)
Footwall without shears (58)	Strainbursts located in the footwall (55)
Ore (20)	Strainbursts located in the ore or hangingwall (13)

Relations between the displaced tonnage and rockburst categories are analysed in the next section. In order to conduct such analysis, a logarithmic damage index was developed to quantify the level of damage at a specific location, Table 4. This index was based on the tonnage of material displaced by rockburst at a particular location. A very similar index was used by Heal (2010).

Table 4 Empirical rockburst damage index based on the displaced tonnage

Rockburst Damage Index	Range
0 – No damage	0 tonne
1 – Minor damage	0–1 tonne
2 – Moderate damage	1–10 tonnes
3 – Important damage	10–100 tonnes
4 – Major damage	100–1,000 tonnes
5 – Extreme damage	>1,000 tonnes

3.3 Influence of geospatial distribution of rockbursts and seismic source characterisation on displaced tonnage

Rockbursts were regrouped based on the geological unit where damage was located. Damage locations in the hangingwall and in the ore were characterised by a greater level of mining-induced stress. The presence of shear zones in the vicinity of damage was considered for damage located in the footwall in order to

assess the impact of weaker rock mass quality and movement along these structures on the tonnage displaced during rockburst. The relation between the geospatial distribution of rockburst and the displaced tonnage is presented in Figure 6. The Y-axis corresponds to the proportion of rockburst that belongs to each damage index, for each damage location.

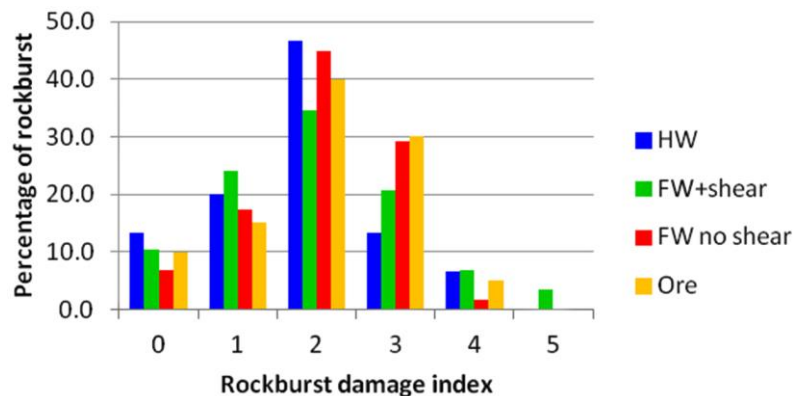


Figure 6 Percentage of rockburst per damage index for each category of damage location

Figure 6 demonstrates that a greater proportion of damage that occurred in the hangingwall, the ore, and the footwall close to shear zones is tagged as major or extreme. Damage that occurred in the ore and in the footwall in the absence of shear zones is characterised by a greater proportion of index 3, important damage. The distribution of displaced tonnage appears to be roughly the same at each location for damage indices 0 to 2, no damage to moderate damage. Similitude is observed between damage distributions in the hangingwall and in the footwall characterised by the presence of shear zones. The distribution of damage in the ore zones appears to be correlated with the distribution of damage in the footwall excluding shears for rockburst damage indices 0 to 3. For greater level of damage, i.e. indices 4 and 5, damage in the ore correlates with damage in the hangingwall and in the footwall characterised by shears.

A similar chart is produced in order to analyse the relation between the seismic source characterisation and the displaced tonnage, Figure 7. The distributions observed in Figure 7 appear to be very similar to those observed in Figure 6. These similarities result of the correlation between geological zones and seismic source mechanisms. Fault slip events, whether located in the hangingwall or in the footwall, comprise of a greater proportion of indices 0, 4, and 5 compared to strainbursts. In this case, an index 0 often corresponds to minor bulking of surface support or development of cracks into shotcrete. The observed distribution of displaced tonnage during fault slip events reflects that the severity of these events varies much more than for strainburst events. Damage due to strainbursts can be best grouped into the damage indices 1, 2, and 3, Figure 7.

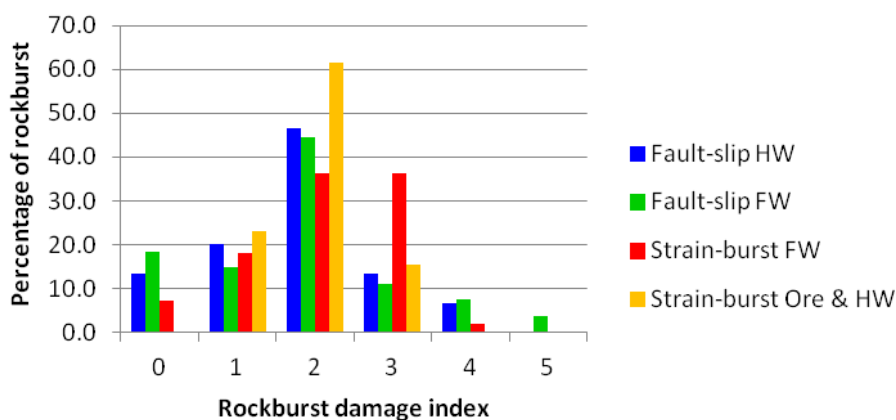


Figure 7 Percentage of rockburst per damage index for each seismic source category

Fault slip events, whether located in the hangingwall or in the footwall, are characterised by similar distributions of damage. On the other hand, the distributions of damage induced by strainbursts differ significantly from the footwall to the other geological zones. Index 3 is significantly dominated by strainbursts located in the footwall. Strainbursts located in the ore or in the hangingwall are largely dominated by damage index 2. A median of 2.7 tonnes is calculated for fault slip events, 7.3 tonnes for strainbursts located in the footwall, and 1.8 tonnes for strainbursts located in the ore or the hangingwall. The damage distributions are well represented by the respective median values.

The distinction between fault slip and strainburst damage distributions confirms that the seismic source mechanism is critical. This is justified due to the different damage mechanisms that generally result from these seismic source mechanisms. Damage resulting from strainbursts is usually characterised by rock bulking due to fracturing while damage resulting from fault slips tends to be associated with seismic shaking, Kaiser et al. (1996).

It is clear that at Creighton, there appears to be a good correlation between geology, geomechanical zones, and rockburst frequency and resulting damage. It is reasonable to believe that it is possible to characterise geospatial zones with distinct probability distributions of demand on support. However, for the analysis of rock support performance, it is more appropriate to focus on levels of damage that can be sustained by support systems. The distributions of displaced tonnage demonstrate that further analysis should focus on damage indices 1 to 3. Indices 4 and 5 represent larger volumes of smaller probability of occurrence. The remaining categories of damage are characterised by a better distribution of strainburst induced damage. This in addition to the better quality of strainburst data discussed in Morissette et al. (2011) demonstrates the importance to focus on the analysis of strainbursts to design support guidelines.

3.4 Influence of magnitude and distance on the interpretation of seismic source mechanism and displaced tonnage

Figure 5 demonstrates that the seismic source mechanisms at Creighton can be characterised by different levels of magnitude and distance between the seismic source and the resulting damage. For example, fault slips appeared to be positively correlated with both the distance and magnitude in PC1. Figure 8 illustrates the relation between the magnitude of seismic events and the distance between seismic sources and associated damage. On Figure 8(a), rockbursts are colour-coded based on the seismic source characterisation. On Figure 8(b), data are colour-coded based on the rockburst damage index.

The ground motion velocity represented by the peak particle velocity (ppv), is accepted as the most representative parameter to define the dynamic design load (Kaiser et al., 1996). The following scaling law was proposed to approximate the ppv at a given distance from a seismic source in Ontario underground mines (Hedley, 1992):

$$\text{ppv} = 4,000 \left(\frac{R}{10^{M/3}} \right)^{-1.6} \quad (2)$$

where:

- ppv = peak particle velocity (mm/s).
- R = distance from the seismic source (m).
- M = Nuttli magnitude of seismic event.

The relation illustrated in Figure 8(a) validates the analysis of the ground control personnel over the last ten years in correctly identifying the seismic source mechanisms at Creighton Mine. It effectively demonstrates that both the magnitude and the distance were considered consistently. It also demonstrates that it is more difficult to differentiate fault slip events in the footwall from strainbursts based on these two parameters only. However, it was demonstrated with PCA that the presence of a shear zone and the amplitude of damage were also considered by the ground control personnel in order to identify seismic source mechanisms.

Figure 8(a) demonstrate that most rockbursts at Creighton were characterised by a PPV ranging between 30 and 3,000 mm/s, the majority being concentrated between 30 and 300 mm/s. The presence of five outliers is also highlighted by dashed ellipses. It is possible that these rockbursts have not been assigned to the right seismic source. Nevertheless, the majority of rockbursts follow a linear trend on the semi-log chart.

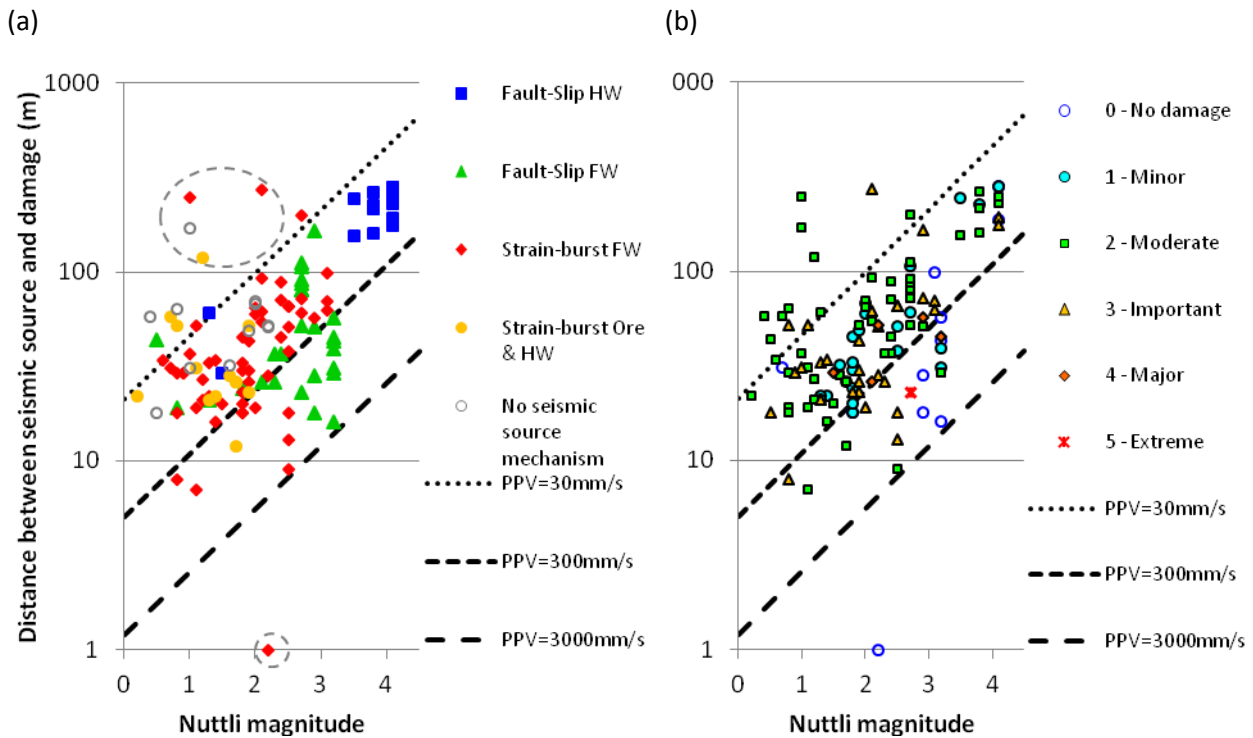


Figure 8 Magnitude–distance relation for rockbursts encountered at Creighton. Rockbursts are colour-coded based on seismic source characterisation (a) and rockburst damage index (b)

Figure 8(b) demonstrates that the relation between the ppv and the displaced tonnage is not as expected. Hedley (1992) proposed that falls of loose ground occur at velocities as low as 50 mm/s, fracturing of intact rock starts at about 300 mm/s, and severe damage at 600 mm/s. These values, although they are included in the range of ppv calculated for most rockbursts that occurred at Creighton Mine between 2000 and 2011, do not appear to be supported by the collected field data. The apparent random distribution of rockburst damage index values demonstrates that the amount of displaced material depends on more variables than magnitude and distance only.

4 Conclusions

This paper reports on the validation of the constructed database of rockburst field data at Creighton Mine, between January 2000 and September 2011. A principal component analysis demonstrated that the data displayed coherent patterns of geospatial distribution of rockburst damage and characterisation of seismic sources.

The investigations undertaken constituted a preliminary effort to quantitatively assess the dynamic load demands on support systems at Creighton Mine. The geospatial distribution of damage and the characterisation of seismic sources were used in order to find different distributions of tonnage displaced by rockburst. Correlations were observed between these parameters, demonstrating the possibility of characterising geospatial zones with distinct probability distributions of demand on support. Geospatial distributions of rockburst could be refined with a more detailed rock mass characterisation and a more consistent assessment of the mine-induced stress at the damage locations.

An attempt to assess the severity of rockburst with the peak particle velocity was presented. Nevertheless, this attempt was not significantly conclusive as the level of damage appeared to be randomly distributed. The result demonstrated that the demand on support systems cannot be characterised by the PPV only.

The assessment of the capacity of support systems will depend on the establishment of a qualitative index based on the damage reported to reinforcement and surface support elements. The assessment of support performance will involve comparing the support capacity to the demand.

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