USE OF MICROSEISMIC MONITORING FOR ROCKBURST MANAGEMENT AT VALE INCO MINES[*]

CEZAR I. TRIFU

Engineering Seismology Group,

Kingston, Ontario K7K 7G3, Canada
trifu@esg.ca

FIDELIS T. SUORINENI

MIRARCO, Laurentian University

Sudbury, Ontario P3E 2C6, Canada
fsuorineni@mirarco.org

Seismic systems provide characterization of mine seismicity and represent a monitoring tool for the management of seismic hazard and rockbursting. Seismic data is employed at all Vale Inco mines in the Sudbury Basin to evaluate and perform mine development activities by optimized stope sequencing, destress blasting and ground support. It is also used for the calibration of numerical models and the identification of major seismically active geological structures for strategic placement of secondary or enhanced support. Seismic monitoring is essential in the assessment and mitigation of seismic hazard and risk, thus minimizing the exposure of equipment and personnel through the use of re-entry protocols.

1 Introduction

The impact of rockbursts on mine operations can be enormous. Economic losses, safety of personnel and destroyed equipment have severe constraints on operations in mines with high seismicity. Minimizing the impact of seismic activity on mining operations may take one of several forms of proactive measures such as tele-remote mining, increased ground support or reinforcement, introduction of new enhanced support systems, and minimizing worker and equipment exposure by use of seismic monitoring systems. Each of these measures requires strategic planning, systematic implementation and a good understanding of the mine seismicity and the mechanism of major seismic events. In recent years an integrated approach using all the proactive measures indicated above has been found more beneficial than the use of any particular element.

Current technology cannot predict when rockburst will occur, and the best we can achieve today is to identify areas of high rockburst potential using numerical models and/or experience. Microseismic monitoring systems have become an integral part of most hard rock deep mines in an effort to characterize mining induced seismicity for a quantitative evaluation of the seismic hazard. These systems have a considerable impact on the mitigation of the seismic risk by minimizing the exposure of personnel and equipment to seismic hazards

---

[*] in *Controlling Seismic Hazard and Sustainable Development of Deep Mines,* C. Tang (ed.), 1105-1114, Rinton Press, New York.

remains. Full waveform Hyperion and Paladin systems, developed and distributed by the Engineering Seismology Group (ESG), are very popular in both the Canadian mines and worldwide.

This paper describes the practical application of seismic systems for the management of seismicity at Vale Inco mines in the Sudbury Basin. Geology and mining activities, including sequencing play major roles in triggering seismicity. Both regional and local mine geology with reference to structural geology play dominant roles in rockbursts occurrence. Because stress changes cannot be avoided in mining, they must be managed through optimum sequencing to minimize their impact. The geology and mining sequences at Vale Inco mines are first presented briefly in the following sections, with a special emphasis on Creighton Mine. Then, the use of the seismic data for the calibration of numerical modelling results and identification of major seismically active geological structures for the strategic placement of enhanced support system are overviewed.

2 Geology

2.1 Regional Geology

The copper-nickel sulphide deposits in Sudbury are part of the Sudbury Igneous Complex (SIC), which forms an elliptical ring separated into the North and South Ranges, which differ with respect to the thickness of the norite and gabbro units, the character of the footwall rock and metamorphic history. The separation between these ranges occurs across a series of ductile shears at the southwestern and southeastern corners of the SIC (Figure 1). The discontinuous sublayer unit of the complex is the usual host for the ore and comprises a series of mafic to ultramafic inclusions of varying size and frequency in a matrix of norite and sulphides. Orebodies generally have a high-grade footwall with a gradational lower-grade hanging wall.

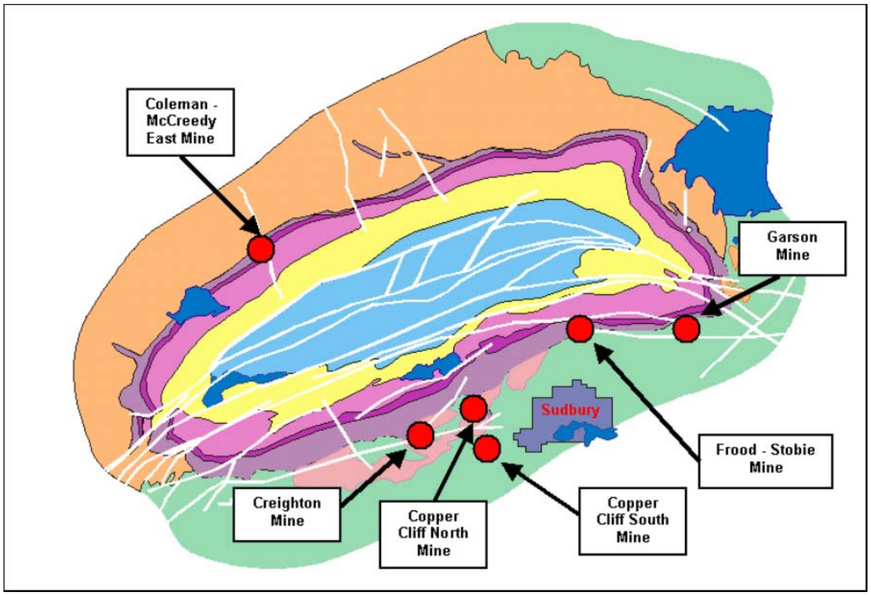


Figure 1 Location of Vale Inco mines in the Sudbury Basin.

The rocks of the SIC are affected by five major fault sets, as follows [1]: (1) A major, south-dipping, curvilinear, reverse fault set trending ENE-NW, exiting the basin at its SW and SE corners. These faults are part of the Penokean Orogeny that occurred between 1870 and 1700 Ma. (2) A set of steeply dipping NNW trending faults cuts the North Range and crosscuts the mineral deposits at Coleman Mine, with a mostly sinistral displacement of up to 1000 m on the Fecunis Lake Fault. (3) Another set of faults cuts at a shallow angle on the East side of the basin. These faults have a sinistral displacement of up to 700 m. (4) The Murray system consists of E-W trending, steeply-dipping faults that cut the South Range and have right lateral displacement. (5) A late-stage set of faults and fractures formed by the current tectonic stress field, infilled with low-temperature sulphides and carbonate minerals. These structures exhibit low microseismicity and are sometimes associated with poor ground conditions.

Two major dyke swarms are apparent: (a) A system of quartz diabase dykes striking E-W along the southern margin of the basin, varying in thickness from a few inches to several tens of meters, commonly referred to as “trap” dykes. The quartz diabase dykes cross-cut several mineral deposits at Creighton Mine. (b) A system of olivine diabase dykes, commonly referred to as the “Sudbury Swarm” that strike NW-SW and are steeply dipping, dated at about 1235 Ma. Note that this system is offset by fault sets 2 to 4 above.

2.2 Local Geology

Most orebodies at Vale Inco mines are commonly intersected by different geological structures or dykes, which affect the overall mining induced stress and rock mass behaviour. To exemplify this, we will discuss in detail the situation of Creighton Mine, located within the Creighton embayment, on the outer rim of the South Range of the SIC (Figure 1). This embayment includes two smaller satellite embayments to the west called Gertrude and Gertrude West. Creighton Fault, which strikes N70°E and dips 85°N, truncates a small, near-surface portion of the Creighton embayment at its southern margin.

Four main geological units have been identified in the mine: (1) Basal norite, towards the base of the main SIC, overlying the embayment, which contains a small percentage of inclusions and disseminated sulphides. (2) Sublayer norite, the common ore host, consisting of sulphide inclusions of varying composition, size and frequency of occurrence. (3) A short, variably mineralized, quartz diorite offset dyke. Mineralization is spatially associated with the dyke, but he dyke itself is usually barren. (4) Footwall rocks comprising Creighton granite that intrudes lower Huronian metavolcanics and metasediments.

Mineralization is contained within a NW plunging embayment of norite into the footwall and is controlled by two troughs or indentations (Figure 2). The majority of orebodies are located along one of these troughs (Creighton 400 trough), plunging towards NW and following the general geometry of the main Creighton embayment, while the remainder are located along a near orthogonal trough (Gertrude 402 trough) plunging NE at 40 degrees.

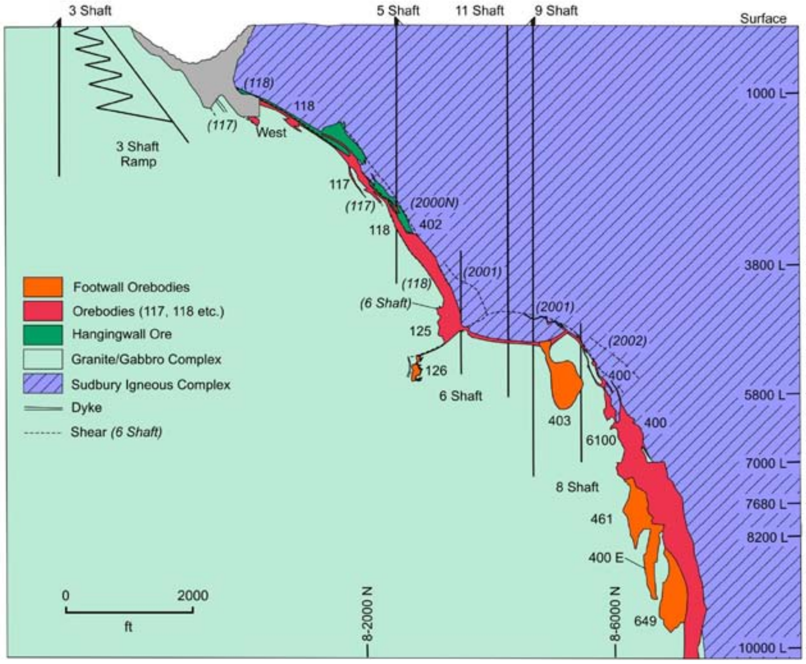


Figure 2 Composite geology section of Creighton Mine [2].

At depth, the Creighton main orebody strikes roughly E-W and dips steeply to the north. Along strike, the bulk of the remaining orebody extends about 150 m with an average thickness of 100 m. At a depth of 2295 m (7530 ft) the ore zone extends about 250 m E-W with an average thickness of 50 m. In addition, there are several ore zones located in the hangingwall and footwall of the main orebody at depth. Creighton Mine comprises 15 orebodies of which the majority of the higher grade mineralization in the Main, West, 117, 118, 128, 125, 126, and 401 orebodies has been depleted. Remaining reserves and resources are concentrated in the 3 Shaft remnants, Deep 400, Up-dip 402, 403 remnants and the recently discovered 649 orebody [1].

2.3 Characteristic of Major Rock Units

The mining zone at Creighton can be characterized as footwall granite-gabbro domain, massive sulphide ore zone domain and hangingwall norite domain (Figure 2). Other ore zones, such as the 461 orebody, are embedded in the footwall granite-gabbro domain.

Structural analyses identified mostly two subvertical joint sets and one low angle to flat lying joint set in the footwall domain. The joint set orientation in the hanging wall norite domain is different with three high angle to subvertical joint sets and a low angle joint set. There are four joint sets in the ore domain with three subvertical joint sets and one low angle to flat lying joint set. Table 1 summarizes the intact rock properties from all three rock domains.

Table 1 Average geomechanical properties of major units at Creighton Mine.

Domain	Density (Kg/m^3)	UCS (MPa)	Young Modulus (GPa)	Poisson ratio (ν)
Granite	2600	240	60	0.26
Norite	2850	190	78	0.28
Ore	3600	130	68	0.25

Systematic logging and mapping have been carried out over the last few years to identify major joint sets and structures. Core logging data is processed by external consultants using procedures developed internally by Vale Inco. The derived results are regularly employed to identify the distribution of rock mass quality and location of major structures for design purposes (e.g., stope design, support design, location of major infrastructure).

The pre-mining far-field stress regime used in the Sudbury Basin is derived from far-field stress measurements taken in the mid to late 1980s. In the absence of more recent measurements, the stress tensor used for numerical modelling at all Vale Inco mines is derived from these measurements and field observations. In general, the major principal stress is horizontal and trending E-W. The minor principal stress is vertical (Table 2). With mining going deeper it is appropriate to update the mine far filed stress tensor. A number of in-situ stress measurements using acoustic emissions were tried in the last years with inconclusive results. More work is needed in this area since this method is inexpensive and relatively fast.

Table 2 Stress tensor used for the numerical modelling (Z is depth in meters).

Stress	Magnitude (MPa)	Trend (^{o})	Plunge (^{o})
σ_1	10.9 + 0.0407 Z	270	0
σ_2	8.7 + 0.0326 Z	0	0
σ_3	0.029 Z	90	90

3 Mining Activities

Vale Inco mines have been in operation for over 100 years in the Sudbury Basin. At most mines exploitation started with open pits and underground mining at shadow depths. In 1940s for example, mining was very labour intensive, with small access and timber support. The 1960s signal early mechanization and introduction to mechanical bolts as mining extends to 900 m depth. Mechanized mining with remote equipment became available and operations reached 1800 m depth. Rebars, cables, mesh wire and shotcrete were introduced. The widespread use of the above support systems, through mechanized bolters, allowed the mining to extend to 2200 m depth a decade later. Meanwhile, mine design was introduced in the 1990s, including standard distressing, blast scheduling and numerical modelling, allowing for pillar less sequence and mining through fill. In the 2000s mining reached 2400 m depth, new support was developed, such as the cone bolts, zero gauge straps and shotcrete arches. New mining techniques have been implemented such as the pillar less center out mining sequence, the development sequence and orientation, and the mining rate control.

Over the years, various mining methods were employed to extract the ore from these Vale Inco mines, including shrinkage, sub level caving, block caving, cut-and-fill, vertical crater retreat and slot-and-slash mining. Slot-and-slash is the principle mining method used at all mines, with the exception of Coleman and Stobie Mines, which are using the cut-and-fill and sub-level caving, respectively. Backfill of mine stopes uses mainly mill tailings mixed with water and cement in the sand fill plants and delivered through a series of boreholes and 4-inch sand fill lines to the mined stopes. Garson Mine mainly employs a paste fill system, whereas Copper Cliff North Mine uses a combination of sand fill and cemented rockfill.

Presently, mining activities take place between 300 and 2400 m below surface. Most operating shafts reach down to 1200 m, while the deepest shaft is Creighton’s Number 9 shaft with access to the 2135 m level (7000 ft). Below this depth, Creighton has adopted an incremental strategy to reach the ore below shaft's bottom via a haulage ramp system.

4 Monitoring of Mine Seismicity

Historically, the first documented seismic events and rockbursts were observed at Creighton Mine in the 1930s, predominantly in crown and sill pillars at a depth of 700 m (2300 ft). Over time, seismicity began to occur in single development headings (i.e., strain bursts) at a depth of 1200 m (4000 ft) and in sill accesses following production blasts at a depth of 2000 m (6600 ft). Most rockbursts in sill accesses occurred due to the day to day mining activity and have typically been the result of sill and crown pillar mining (pillar bursts), whereas most strain bursts have been associated with geological structures.

Figure 3 presents the number of seismic events with magnitude larger than 2 occurred during each of the last five years [3] at each of the six Vale Inco mines in Sudbury. Worth noting, 266 seismic events or 80% of the total 332 large events were generated by fault slips and only 20% were caused by pillar bursts. If the large magnitude seismicity at Creighton Mine was known, the increase in the large magnitude events at the rest of the mines indicates a new trend, most likely associated with the development of their mining operations, particularly increase depths and extraction rates.

The rock mechanics group at Vale Inco initiated a systematic approach for the management of seismicity and rock bursts by investing in a number of initiatives depending on the situation. These initiatives include: (a) Use of detailed numerical modelling for the understanding of rock mass behaviour. (b) Testing and implementation of a number of burst prone support systems at various mines. (c) Implementation of stope de-stressing in high stress areas (e.g., 461 orebody at Creighton Mine). (d) Adapt development procedures and support systems to particular ground such as in proximity to major dykes, faults and shears. (e) Increase use of microseismic systems and expansion of the seismic sensor array coverage within individual mines. (f) Use of 3D Virtual Reality Laboratory (VRL) for better understanding of mine seismicity. This has resulted in the development of a hazard map procedure used to identify areas of high hazard and risk [4].

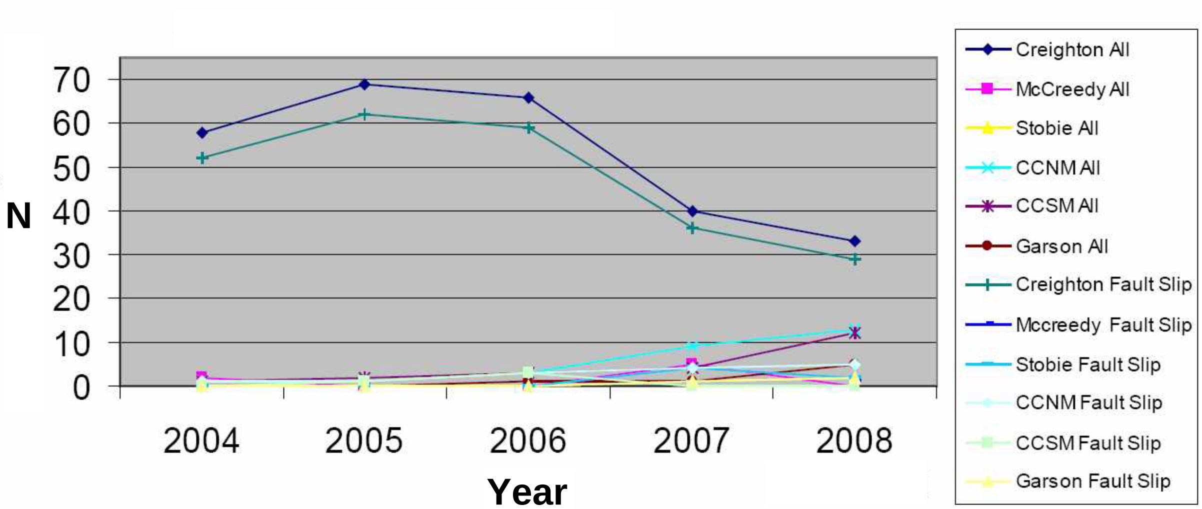


Figure 3 Number of seismic events with magnitude ≥ 2.

Associated with the long history of mining in Sudbury are stress-induced and structurally generated seismic activities, as well as the evolution of seismic monitoring systems. The first microseismic system in the Sudbury Basin was a 16-channel MP250 manufactured by Electrolab (Spokane, WA). installed in 1980 at Creighton Mine, later expanded to monitor increased seismicity at depth. Similar systems were subsequently installed at Copper Cliff North, Stobie, Levack and Crean Hill Mines.

Table 3 Seismic monitoring systems at Vale Inco mines.

Mine	**Development Max. Depth (m / ft)**	**Production Max. Depth (m / ft)**	**Micro-seismic System**	**No. Channels**	**No. Tri-axials**	**Strong Motion System**	**No. Sensors**	**Re-entry Protocol**
Creighton	3420 / 7940	2380 / 7810	Hyperion	104	11	Paladin	4	Seismic Work
Coleman	1660 / 5440	1550 / 5080	Hyperion	96	9	Paladin	3	Event Rate
Copper Cliff North	1525 / 5000	1280 / 4200	Hyperion /Paladin	100	7	Paladin	1	Seismic Work
Copper Cliff South	1525 / 5000	1320 / 4330	Paladin	60	6	Paladin	1	Seismic Work
Frood Stobie	1200 / 3930	1100 / 3600	MP250	32	0	Paladin	0	Event Rate
Garson	1555 / 5100	1525 / 5000	Hyperion	32	0	Paladin	1	Event Rate

The original MP250 system installed at Creighton Mine was converted in 1988 into a 12-bit full waveform system developed by Queen's University as part of the Canadian Rockburst Research Program. This system employed the accelerometer array already in operation underground, but improved first arrival picking and with them both event location and magnitude estimates. In 1999, the seismic system was replaced by a 16-bit Hyperion system developed by the Engineering Seismology Group (ESG, Kingston, ON). This is a central acquisition system with trigger based recording. Hyperion microseimic systems were installed and regularly expanded at Garson, Coleman, Copper Cliff North, Copper Cliff South and Creighton Mines. The sensor array consists typically of uniaxial accelerometers with a sensitivity of 30 V/g and a frequency range of 50 to 5000 Hz, and triaxial accelerometers with sensitivities of 0.3 and 0.5 V/g, and a frequency range of 3 to 8000 Hz.

Although microseismic systems can locate any seismic event within the mine, the magnitude estimates are limited to events between -2 and 1. For larger magnitude events all sensors of these arrays will clip. Consequently, in order to correctly estimate the magnitude of larger events, mines operate one or more triaxial 4.5 Hz geophones recorded by a 24-bit Paladin system, also developed by ESG (Table 3). Paladin is a distributed acquisition system with continuous and trigger based recording, designed to replace the older Hyperion architecture [5]. Over time, it will replace the older systems as needed.

5 Management of Seismicity and Rockbursting

Elevated stresses in mines can cause both strain bursts around rockmass openings and structurally-induced seismicity along structures. The latter can result when elevated stresses lead to the destruction of rockbridges in discrete geological planes of weakness, fault slip or fracture propagation (Figure 4). Contrary to conventional representation, most geological structures such as faults are not continuous but contain intact rockbridges either linearly or in an en-echelon format. Destruction of intact rock can occur in major discrete or stepped continuous geological structures [6].

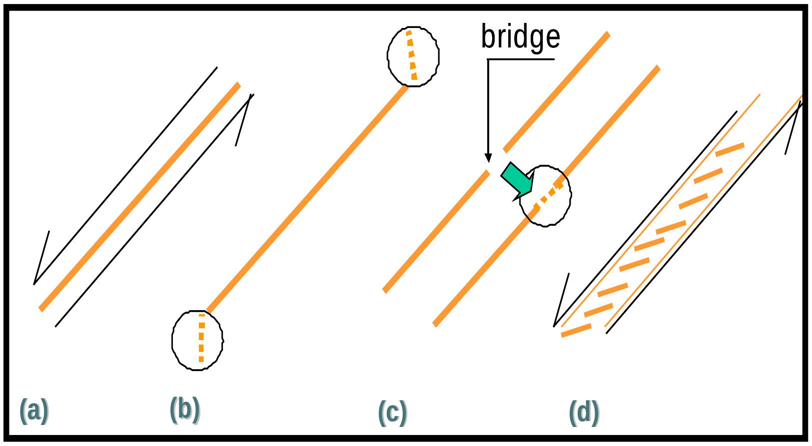


Figure 4 Conceptual rockburst mechanisms: (a) slip along continuous fault, (b) fracture propagation, (c) damage of rockbridges co-linear with faults, and (d) damage of en-echelon rockbridges in apparently continuous discrete fault.

Seismic monitoring systems identify, locate and quantify mine seismicity, allowing for a better understanding of the rockbursting mechanism. As such, they contribute to the management and mitigation of seismic hazards, for improved worker safety and enhanced mining productivity. In the following, various aspects of this management are discussed, such as mining development strategy and ground support, use of seismicity for the calibration of numerical models, and the evaluation of restricted access and re-entry protocol.

5.1 Mine Development Strategy and Ground Support

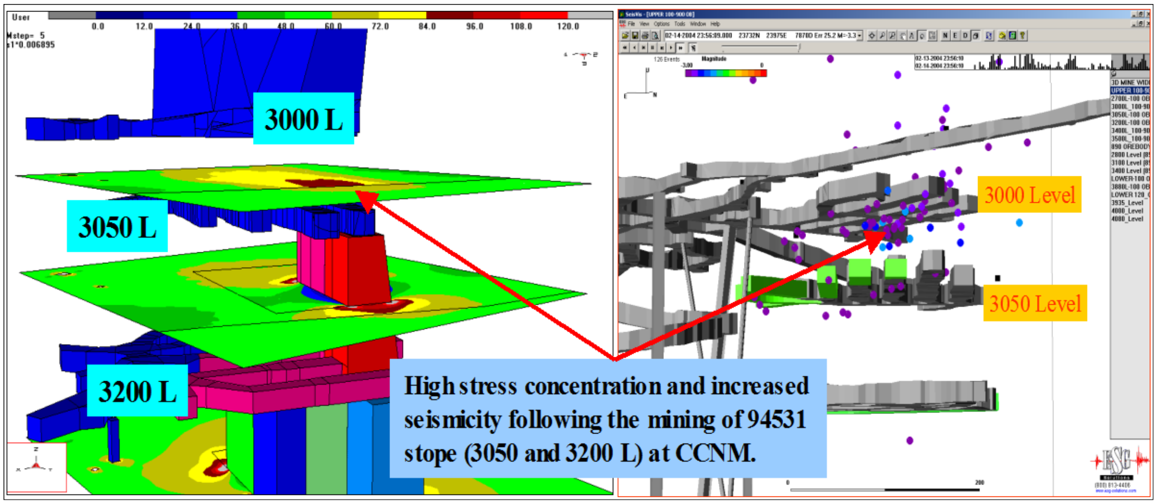
Rockmass damage is typically tied to high stresses and the presence of geological structures, sometimes quite remote from mining activity. Stress-induced seismicity in intact rock around excavations (strain bursts) is well managed for development activities through optimized stope sequencing, destress blasting and good ground support practices. The deepest mining in the region is carried out at Creighton Mine, where top sills are developed below a depth of 2135 m (7000 ft) underneath or within previously mined and backfilled zones. The ground is supported with a first layer of shotcrete, followed by a layer of split set bolts and screen, and finished with a second layer of shotcrete. The development is done in short, 1.8 m (6 ft) rounds.

Ground support system is continuously improved based on trials and analyses of the ground response and stress levels, confirmed through the monitoring of increased mine seismicity. A combination of cone bolts with zero-gauge straps or shotcrete arches is employed for enhanced support, proven very effective in burst-prone conditions and around seismically active geological structures, especially when installed during development or at the early stage of mining. With the exception of development in damaged ground (under sandfill), all deep development follows a strict perimeter and destress blasting to reduce the number of strain bursts in the development headings [1].

5.2 Calibration of Numerical Modelling

Numerical modelling is an integral part of both short and long term mine planning. Modelling software includes three-dimensional elastic packages (Examine-3D, MAP3D) and finite element codes (3DEC, FLAC-3D). MAP3D has been used at Vale Inco since the 1990s. Being easy and quick to use it became a valuable tool for the Ground Control Engineer to employ in mine planning and stope sequencing. The mine’s stope model can be easily expanded to include new mining areas and the results can be rapidly compared against years of empirical data.

Figure 5 shows the numerical modelling results across the crown pillar between the 3000 and 3050 levels at Copper Cliff North Mine after mining of the 94531 stope between the 3050 and 3200 levels (left). These results outline a high stress zone defined by the major principal stress greater than 100 MPa contour. Seismic data is often used as a calibration tool to adjust the parameters of the numerical model until a good correlation is obtained between the areas of high stress and burst potential and occurred seismicity. Seismic data in the crown pillar after the actual mining of the stope is shown on the right side of Figure 4. The strong correlation between the high stress region and recorded microseimicity is apparent, which gives confidence in the use of such a numerical model for the stress and rockburst management.



High stress concentration and increased seismicity following the mining of 94531 stope (3050 and 3200 L) at CCNM.

Figure 5 Modelling results (left) show strong correlation with seismic data (right) at Copper Cliff North Mine.

5.3 *Seismic Active Structures and Hazard Assessment*

Not all geological structures are directly observed and mapped. Moreover, it is the occurrence of seismicity that characterizes if a geological structure is active. Both the individual characteristics and number of geological structures or seismically active planes (SAP) with rockburst potential is critical for a reliable evaluation of the seismic hazard to mining operations. Microseimicity related to these structures is also evidence of rockmass degradation from elevated stresses as each microseismic (MS) event indicates rock fracturing. Rockbursts also generate dynamic stress waves that cause damage to the rockmass, extent of which depends on the peak particle velocity (ppv) level. Individual hazard maps can be generated for each of these three factors, MS, SAPs and ppv, as well as for combined factors. An example of a combined seismic hazard map is shown in Figure 6 [7].

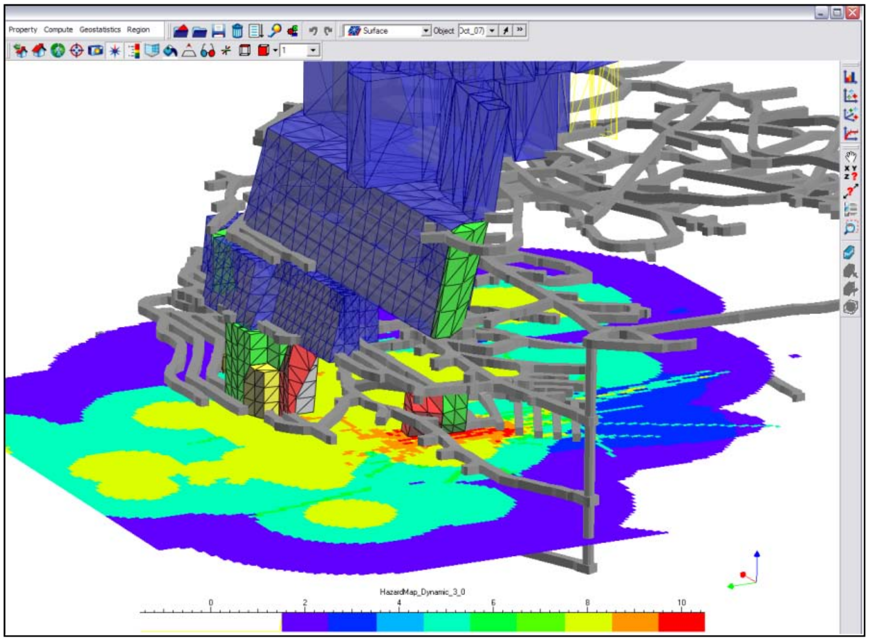


Figure 6 Composite hazard map at Creighton Mine based on MS rockmass degradation, presence of and number of SAPs and ppv, assuming the occurrence of a magnitude 3.0 seismic event (color scale from 1 to 10).

Hazard maps can be used for (i) support selection and tracking of rockmass condition for excavation support rehabilitation, and (ii) future mine development planning by locating infrastructure away from hazardous areas, if practical, or by installing stronger support in these areas if they cannot be avoided. Hazard maps need to be continuously calibrated against underground observations to include existing rockmass conditions and support effects at the time of bursting. More work is required for automated generation of hazard maps for daily, routine application at mines [8].

5.4 Re-entry Protocol

Since 1980s, mine seismic systems have been used to monitor the seismic activity by providing the time, location and magnitude of the occurred events. At first, mine management would close down an entire level or a number of levels after a large event and would wait until the seismicity decayed to background noise in the affected area. Then, technical and operating staff would visit the affected areas to assess if any damage occurred and what type of reconditioning is required. With the increased performance of the monitoring systems, locations and magnitudes of significant events became more accurate. Such information is essential to guarantee that workforce is safely routed and not sent in the harm’s way and to allow for restrictions to be defined to smaller and more-specific areas, rather than entire levels.

Number of events per hour has guided the management on when and where to remove personnel. At times, seismic events occur in the vicinity of underground excavations, in which case access to some areas is temporarily restricted. When the seismicity decreases to background levels, these areas are deemed safe and investigation personnel are permitted to re-enter in order to assess for damage and stability issues. Information is rigorously communicated to the affected crews and mining personnel with details on (i) seismic intensity (i.e., number of events per hour), (ii) location and magnitude of the seismic event, (iii) any restricted access and damage.

In the last few years, Creighton Mine, followed by other Vale Inco mines, particularly Copper Cliff North and South Mines, developed a process for evacuating areas affected by major seismic events or excessive seismicity. Re-entry to these areas follows an assessment approach based on the energy or seismic moment release, developed and calibrated from historical data in partnership with ESG (i.e., Seiswatch). This tool plays an important role in identifying and isolating areas at risk for the safety of workers. The rest of the mines are using event rates for the re-entry protocol and are at the development stage of procedures similar to those in use at Creighton, Copper Cliff North and South Mines.

Figure 7 depicts a typical response curve for the seismic moment (Seismic Work) parameter. The red line indicates the data for seismic events following a large burst, the red dashed line indicates the regression for the past 4 hours of data, the purple line indicates the curve for a ‘typical’ large event, and the blue line indicates the slope derived during ‘normal’ or background seismicity. Three main phases are shown: the initial steep slope indicates a period of instability after the event, followed by a transition period, and the return to stable conditions.

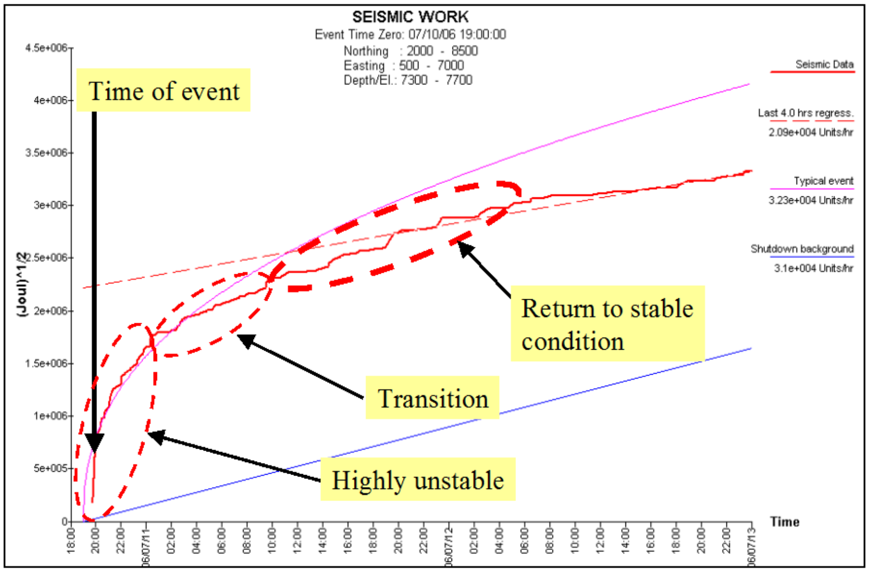


Figure 7 Seismic Work as a function of time.

6 Conclusions

The presence of mining activities in the context of regional and local geology invariably leads to stress redistribution. Rockmass response to this stress redistribution manifests as mine seismicity. The response can sometimes take the form of rockbursts, which can have a considerable impact on mining operations, including potential loss of resources, damage to equipment and even loss of life. Seismic monitoring systems allow for a quantitative characterization of seismicity, thus providing the means for the management of seismic hazard and rockbursting. Worth noting, all Vale Inco mines in the Sudbury Basin operate such seismic monitoring systems.

Seismic data is routinely evaluated for mine development activities through optimized stope sequencing, destress blasting and ground support. Support practice is continuously improved based on trials and analyses of the ground response and stress levels, confirmed through the monitoring of seismicity. Seismic data is also used for the calibration of numerical models. Thus, model parameters are adjusted until a good correlation is obtained between observed seismicity and expected fracture modelling results. It is through calibrated models that potential locations of future rockbursts are estimated. Furthermore, seismic monitoring allows the identification of major seismically active geological structures for strategic placement of secondary or enhanced support.

In view of published scientific results to date, this study cautions against the application of seismic monitoring for rockburst prediction purposes, as this can be misleading and with disastrous consequences. Instead, it underlines the use of the seismic technology as a monitoring tool, which can be employed effectively in the assessment and mitigation of seismic hazard, similar to its use by civil engineers in establishing design requirements and building codes. By minimizing the exposure of equipment and personnel to seismic hazards, through the use of re-entry protocols, seismic systems have also a considerable impact on the mitigation of seismic risk.

Acknowledgments

The authors would like to thank Farid Malek (Vale Inco Ltd.) for his inspirational discussions that led to the present study, as well as for his suggestions throughout a critical review of the manuscript.

References

1. Malek, F., Suorineni, F.T. and Vasak, P. Geomechanics strategies for rockburst management at Vale Inco Creighton mine, *ROCKENG09: Proceedings of the 3rd Canada-US Rock Mechanics Symposium*, M. Diederichs and G. Grasselli (eds.), Paper 4234, 12 pp, 9-15 May 2009, Toronto, Ontario.
2. Malek, F., Trifu, C-I., Suorineni, F.T., Espley, S. and Yao, M. Management of high stress and seismicity at Vale Inco Creighton Mine, *Proceedings of American Rock Mechanics Association General Assembly*, ARMA 08-386, 8 pp, 29 June to 2 July 2008, San Francisco, California.
3. Thibodeau, D. Fault slip event issue, *CEMI Fault Slip Workshop*, 14-15 May 2009, Toronto, Ontario.
4. Kaiser, P.K., Vasak, P., Suorineni F.T. and Thibodeau, D. New dimensions in seismic data interpretation with 3-D virtual reality visualization for burst-prone mines, in *Controlling Seismic Risk*, Y. Potvin and M. Hudyma (eds.), pp. 33-45, Australian Centre for Geomechanics, Perth, Australia, 2005.
5. Alexander, J. and Trifu, C-I. Monitoring mine seismicity in Canada, in *Controlling Seismic Risk*, Y. Potvin and M. Hudyma (eds.), pp. 353-358, Australian Centre for Geomechanics, Perth, Australia, 2005.
6. Vasak, P, Suorineni, F.T. and Verma, A. Identification of seismically active structures for hazard assessment at Creighton Mine, *Report to INCO Technology Centre*, 114 pp., 2004.
7. Vasak, P. Creighton hazard map project, *Internal Report to Vale Inco Creighton Mine*, 108 pp., 2008.
8. Trifu, C-I. and Shumila, V. Seismic hazard assessment in mines using a marked spatio-temporal point process model, in *Controlling Seismic Risk*, Y. Potvin and M. Hudyma (eds.), pp. 461-467, Australian Centre for Geomechanics, Perth, Australia, 2005.