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Practical applications of a rockburst database to ground support design at LaRonde Mine

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Abstract

Agnico Eagle's flagship LaRonde Mine is exploiting a world class Au-Ag-Cu-Zn massive sulphide lenses complex. It is located in the Abitibi Region of northwestern Quebec, approximately 650 km northwest of Montreal. With more than 4 m oz of gold in proven and probable reserves, LaRonde has one of the largest gold deposits of any mine operating in Canada. These reserves extend from surface down to 3,110 m and remain open at depth. LaRonde's ore production is around 6,300 t per day with the current mining operations taking place at 2,930 m below surface.

Seismicity has been recorded at LaRonde Mine since 2004. Seismic events have caused damage to the underground excavations but have not resulted in personnel injury. This paper presents a critical review of the reported rockburst damage and how this information was used in adapting the ground support design for LaRonde. The use of the LaRonde rockburst database along with the mine seismic history has led to a more reliable evaluation of the seismic risk for specific excavations. This has led to a proactive strategy of upgrading ground support prior to the occurrence of significant seismic events in areas of concern.

1 Introduction

Agnico Eagle Mines Ltd. is a gold producer with six producing mines in three different countries. LaRonde Mine is located in the town of Pressiac in northwestern Quebec. It is the company's flagship mine and achieves a steady production of 6,300 t per day using the 2,250 m Penna Shaft. Historically production has comes from three different lenses with zone 20 providing the majority of the ore which is still true today.

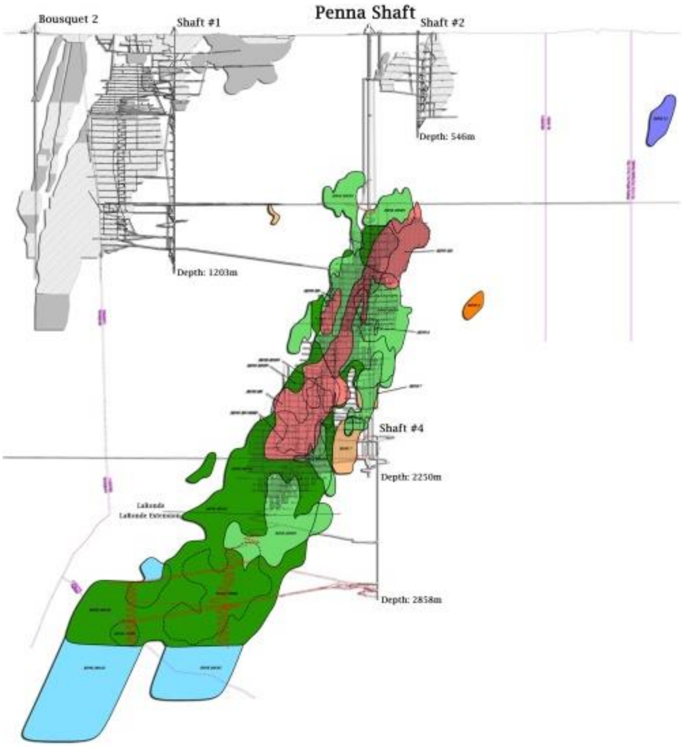

Figure 1 Longitudinal view of LaRonde Mine

The mine life has been estimated to 2025 with 3.88 m oz of proven and probable gold reserves (Agnico Eagle Mines Ltd. 2014). The orebody is polymetallic; zinc, copper, lead and silver are produced as by-products. Over 12 km of lateral development has been planned in 2014. A mine extension was approved in 2006 to extract the orebody between 2,450 and 3,110 m. A winze has been sunk to extract the ore from this new horizon. In October 2013, the first stope was blasted at the 293L (2,930 m below surface). A longitudinal view of LaRonde Mine can be seen in Figure 1.

1.1 Geology and field stresses

The in situ stresses are estimated by the equations provided in Table 1 and based on the depth below surface (DBS). As an indication, calculated values at the elevation of 2,150 m below surface (215L) are given.

Table 1 Stress gradients at LaRonde Mine

Component	Equation	215L	Plunge/direction
σ_1	8.62 + (0.04 × DBS)	95 MPa	0°/000°
σ_2	5.39 + (0.0262 × DBS)	62 MPa	0°/090°
σ_3	0.0281 × DBS	60 MPa	-90°/000°

With the new development in the deepest part of the mine, laboratory tests have been performed on different rock types. The intact strength of rock types found at LaRonde is relatively good for the majority of the rock types (Table 2). The mechanical behaviour of the rock mass however is further influenced by the presence and degree of alteration.

Table 2 LaRonde mechanical properties of intact rock (290L)

Rock type	UCS (MPa)	E (GPa)
Basalt	100	50
Rhyolite	260	66
Rhyodacite	200	63
Semi-massive sulphide	200	70

Typically, permanent infrastructures are developed in the basalt host rock. However, the majority of haulage drifts and drawpoints are developed in rhyolite/rhyodacite which are characterised by a tightly (centimetre to decimetre) spaced foliation dipping approximately 75-80° towards the south and parallel to the orebody (Langevin & Turcotte 2007). These units are also characterised by localised sericite alteration zones. In the new 293 horizon (2,900 m below surface), alteration is less present and the rock mass is more silicified resulting in a more brittle behaviour.

2 Rockburst history at LaRonde

Ortlepp (1997) defined a rockburst as “a seismic event which causes violent and significant damage to the tunnel or the excavations of a mine”. As a deep and high stress mining operation, LaRonde experiences seismicity on a daily basis attributed to changes in the mining front due to blasting in stopes and development mining. Since the beginning of the operation, LaRonde has observed 61 rockbursts between 1999 and 2013 (Figure 2). In 2007, the mining of three highly stressed sill pillars generated a large number of rockburst events.

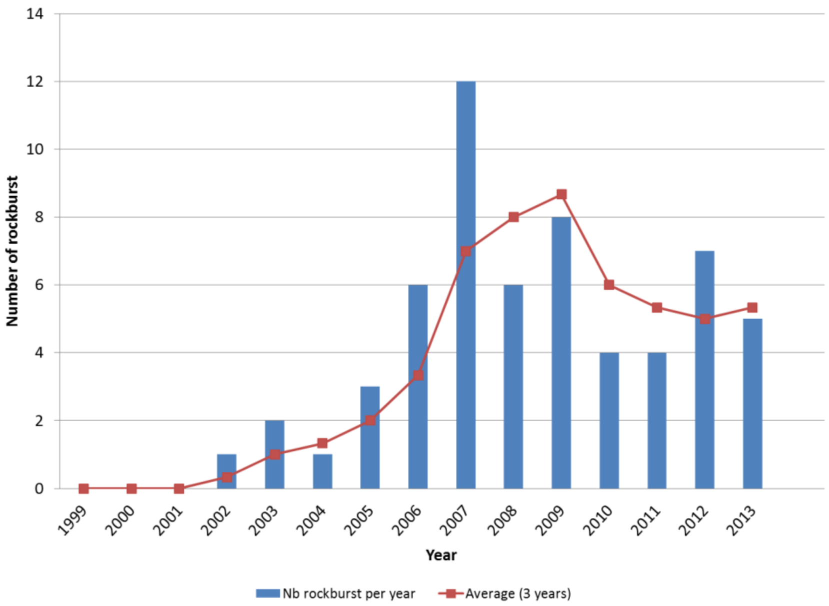

Figure 2 Number of rockburst since the beginning of the operation in 1999

Each rockburst was classified based on the rockburst damage scale (RDS) from Heal et al. (2006). Table 3 shows the distribution of recorded rockbursts based on the estimated of weight of rock displaced by the seismic event. Since the beginning of mining at LaRonde, 70% of the rockbursts have displaced less than 10 t.

Table 3 Rockburst damage scale for LaRonde Mine (1999-2013)

Group	Tonnage (t)	Number of rockburst	Average tonnes displaced (t)
R1	< 1	13	0.7
R2	1-10	30	5.5
R3	10-100	9	35.9
R4	100-1,000	13	306
R5	1,000 +	1	1,000

As seismic events are difficult to predict, some rockbursts occurred at times when miners were working underground. Figure 3 shows the cumulative number of tonnes displaced by rockbursts under two different situations. The first curve (whole line) represents rockbursts when there were no workers in the area or zone where damage occurred. This includes areas where no access was permitted as a result of the non-entry protocol issued by the engineering group for stope or development blasts. This also includes downtime of the operation, i.e. when workers are on the surface or at the shaft stations. The second curve (dashed line) represents the rockbursts that occurred when the workforce was underground and potentially exposed to rockburst hazards. With the exception of the first few years of operation of the mine, the majority of significant rockbursts occurred during periods of inactivity where no personnel was exposed. However, in the last two years personnel have been exposed to rock falls, on an average of 5.8 t, associated with rockburst damage.

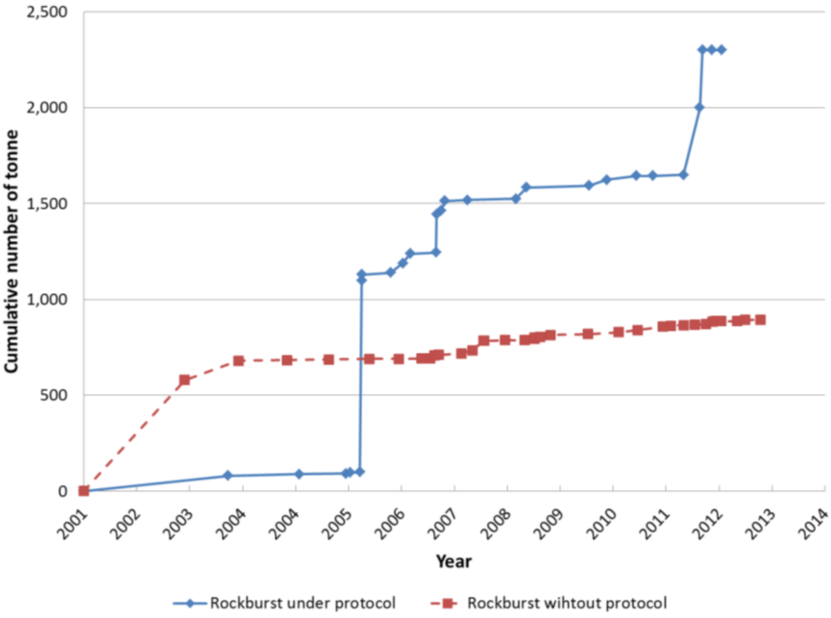

Figure 3 Cumulative number of tonnes displaced from rockbursts with or without personnel exposure

2.1 Mine seismicity at LaRonde

In 2003, an ESG seismic system was installed following a series of rockbursts in 2002 and 2003. Today, this system has been expanded and covers the entire mine. It has 105 channels and is composed of 70 sensors (triaxial/uniaxial) including five surface geophones (4.5 hz) to evaluate the magnitude of large scale events when underground seismic system is saturated by waveform. As the mine is going deeper, seismicity has increased over time (Figure 4). Using the same sensitivity ($M_{Locale} = -1.5$), the seismic system recorded 1,655 events in 2005 compared to 2,687 (+62%) in 2013.

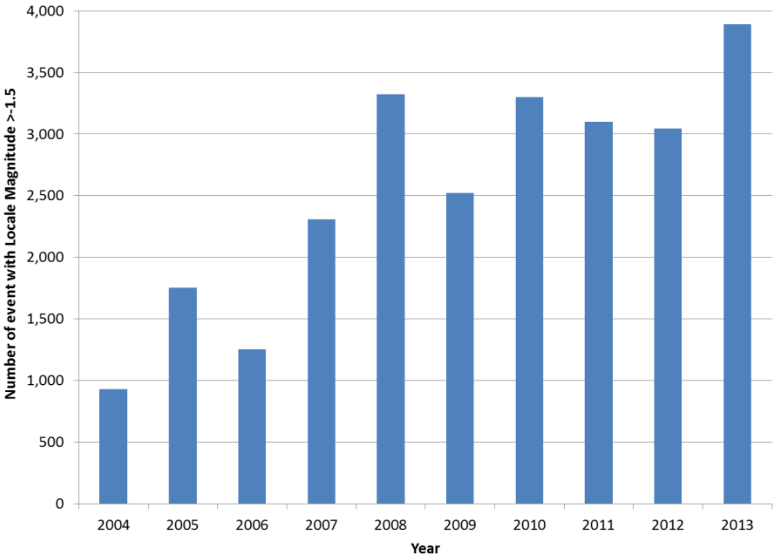

Figure 4 Seismicity at LaRonde Mine between 2004 and 2013 (M_L>-1.5)

The increase in seismicity followed the breakthrough of sill pillars and mining in new horizons. As the principal stress is perpendicular to the orebody, extension of the footprint of the mined out zone had a significant influence on seismicity. Between 2004 and 2013, the operation generated large scale events up to 3.3 Richter Scale. It should be noted that large magnitude events are not necessarily proportional to the displaced tonnages at LaRonde. Figure 5 shows the cumulative tonnage displaced at the mine and the peak particle velocity (ppv) in m/s. The ppv from a seismic event can be estimated with the Kaiser et al. (1996) equation:

$$PPV = 1.4\frac{10^{Mr/_2}}{r} \tag{1}$$

Where:

ppv = peak particle velocity (m/s).

Mr = Richter Magnitude of the event.

r = distance from the epicentre to damage location (m).

A number of large events did not generate major damage on the support of the excavations. The energy released by an event affects the tonnage displaced, but ground support, excavation size, local geology, prior seismic loading, and distance between an event and the damage location are r important parameters that can define the resulting level of damage.

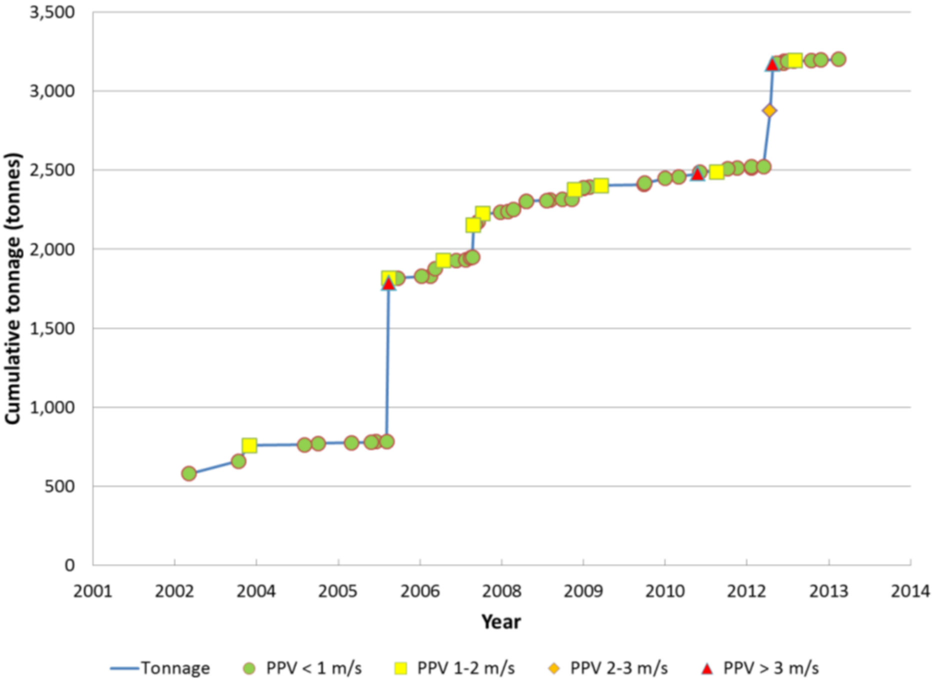

Figure 5 **Cumulative number of tonnes displaced by rockburst with the associated ppv of the event**

2.2 Damage location

Three categories have been developed to characterise the excavation areas where rockbursts occurred at the mine. Table 4 summarises the number of rockburst for each category.

Table 4 **Number of rockburst between 1999 and 2013 at LaRonde for different locations**

Damage location	Number	Percentage
Wall	51	84%
Back	8	13%
Others (raise, floor)	2	3%
Total	61	100%

Only a small percentage of rockbursts, just 13% (Figure 6(b)) resulted in damage to the back of excavations. In general, most of the seismic events causing rockbursts involved wall damage, 84% (Figure 6(a)). This can be explained by the influence of the geological structure on the resistance of the rock mass. LaRonde Mine has a strong regional schistosity that is parallel to the orebody. Walls expose this plane of schistosity and as a result the resistance of the rock mass is reduced due to a reduction in confinement (Figure 7). When energy is released from an event, the deformation wave induces a failure in the rock mass similar to buckling, except in this case failure is essentially instantaneous. As with buckling, rockbursts will usually generate predictable damage locations for the walls: bottom of the north wall and top of the south wall. This is due to the dip of the schistosity which is usually around 80° and follows the buckling corridor (Langevin & Wilson 2013).


(a) (b)

Figure 6 Typical wall and back damage at LaRonde Mine; (a) typical wall damage; (b) typical back damage

The shear force induced in the back and the low confinement of the southern part results in a weak point where back failure tends to occur. In some cases, the propagation of the wall failure during a rockburst will result in damage to the back.

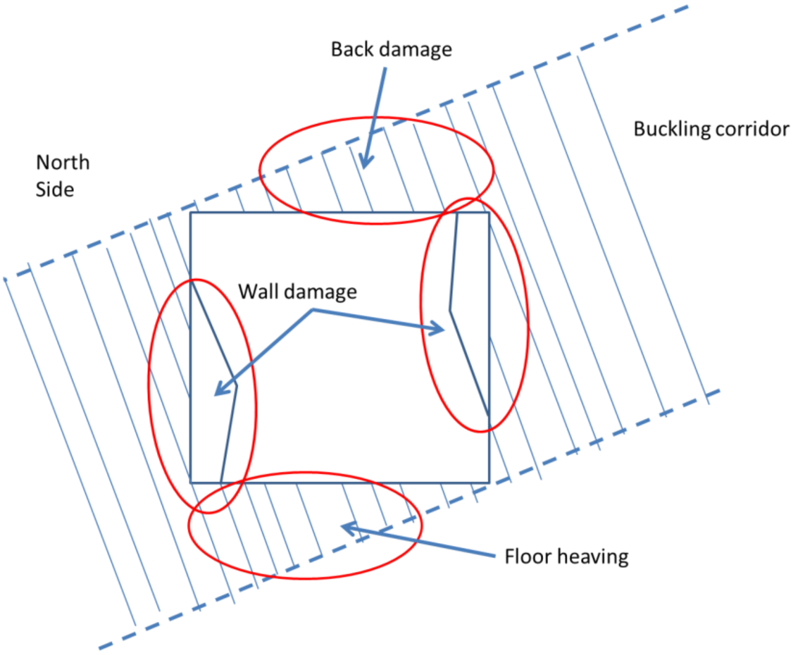

Figure 7 **Damage versus regional schistosity of the rock mass at LaRonde**

2.3 Ground support

Based on past experience the ground support standards have been modified to better deal with seismicity at LaRonde. After a series of rockbursts in 2002 and 2003, dynamic ground support was implemented at LaRonde, originally based on the modified cone bolt (Simser et al. 2007). After an investigation following a large rockburst in 2006 and noting that field observations suggested that the modified cone bolt (MCB) did not perform as intended in foliated ground, the MCB was removed from the ground support standards and replaced in 2007 by the hybrid bolt developed by the mine (Turcotte 2010). This bolt is composed with 2 m friction bolt (Ø39 mm) is installed with the resin already inside the tube followed by an insertion of a 1.9 m rebar (Ø22 mm) (Figure 8).

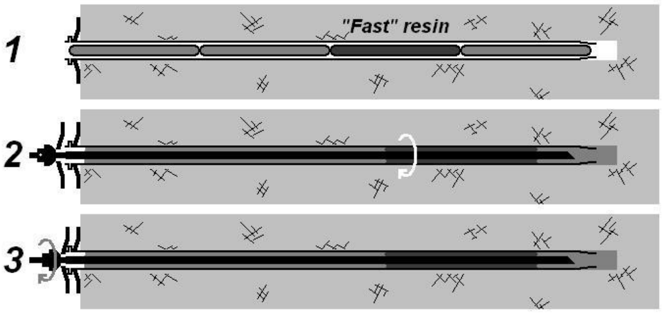

Figure 8 **Procedure used to install the hybrid bolt at LaRonde (after Mercier-Langevin & Turcotte 2007)**

Since 2007, the hybrid bolt combined with 0 gage mine strap continues to be the primary support for dynamic condition at LaRonde. The ground support standards used at the mine have been summarised in Table 5. The number in bracket next to the category is the E2 parameter value from Heal et al. (2006).

Table 5 **Ground support used at LaRonde Mine**

Category	Ground support

	Back	Wall
Unsupported [2]	No support	No support
Standard [5]	Rebar 22 mm × 1.8 m	Split Set bolt 39 mm × 2 m
Dynamic support [15]	Rebar 22 mm × 1.8 m	Split Set bolt 39 mm × 2 m and three horizontal rows of hybrid bolts linked by mine straps (gage 0)
Dynamic support + [25]	Rebar 20 mm × 1.8 m with Garford Cable 6.1 m	Split Set bolt 39 mm × 2 m and three horizontal row of hybrid bolt linked with mine strap (gage 0)

Progression of the ground support strategy had an influence on the number of rockbursts and damage to excavations during the history of the mine. Table 6 summarises the number of rockbursts for different ground support standards and the rockburst damage scale for each of them.

Table 6 Number of rockburst for different ground support since 2001

Ground support	R1	R2	R3	R4	R5
Unsupported	0	1	2	0	0
Standard	6	18	9	4	0
Dynamic Support	1	9	3	1	1
Dynamic support with cable	0	1	0	0	0

A large portion of the damage has occurred when dynamic ground support was not present to contain the ground motion. In 66% of rockburst cases, excavations had a standard support or were unsupported. This is explained by the transition of the dynamic ground support strategy in 2007 with the introduction of hybrid bolt (Figure 9). Today, the standard support is less impacted by rockbursts as it is installed in low rockburst hazard areas of the mine.

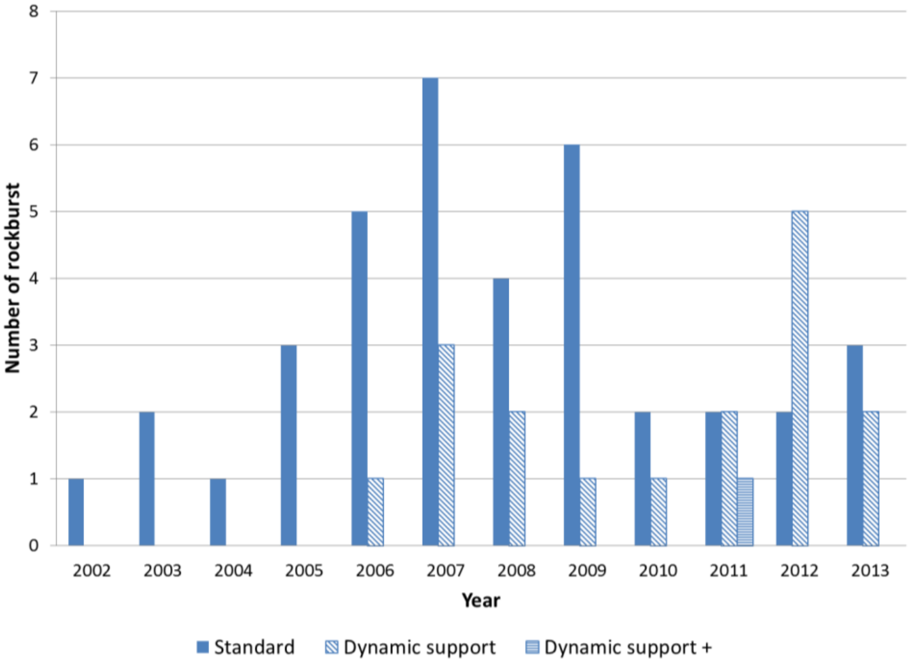

Figure 9 Distribution of the rockburst with ground support strategy per year

2.4 Drift orientation

It has been observed that the orientation of a drift relative to the plane of schistosity has an influence on squeezing ground at LaRonde (Mercier-Langevin & Hadjigeorgiou 2010). The same trend is observed for rockbursts, rockbursts tend to score higher on the RDS when the drift is parallel to the schistosity. Table 7 shows the number of rockburst relative to drift orientation.

Table 7 RDS for different drift orientation in the rockburst database

Drift orientation	R1	R2	R3	R4	R5
0-30°	6	22	10	5	1
30-60°	1	4	0	0	0
60-90°	5	3	4	0	0

Overall, 72% of the rockbursts occurred when the drift orientation was between 0-30° (parallel to the schistosity). This observation is well known at the mine and main infrastructure is designed to be perpendicular to schistosity to minimise the rockburst risk. However, with an orebody that is parallel to the schistosity, it is not practical to eliminate all excavations parallel to schistosity. This is particularly the case in the deep part of the mine where the lateral extension can measure up to 1,000 m.

3 Excavation vulnerability potential

Heal et al. (2006) developed an equation to evaluate excavation vulnerability potential (EVP) of an excavation. The EVP uses different elements like stress regime, intact rock strength, geology, ground support and span to define a number quantifying vulnerability. The equation is:

$$EVP = \frac{E1}{E2} x \frac{\mathrm{E3}}{E4} \tag{2}$$

Where:

E1 = (principal far field stress)/UCS.

E2 = ground support.

E3 = span (m).

E4 = geology.

For E1, the in situ principal stress was used. The value for E2 was modified from Heal et al. (2006). The values are in brackets in Table 5 for ground support standards at LaRonde. For E4, Heal et al. (2006) have defined a value of 0.5 for seismically active major structures, 1.0 for unfavourable rock mass (no major structures) and 1.5 for massive rock mass (no major structures).

To take into account the magnitude of the event and the distance between the damage and event source, Heal et al. (2006) used the far field peak particle velocity (ppv) from Equation (1).

For each rockburst occurring at the LaRonde Mine, an EVP and ppv have been calculated and plotted (Figure 10). Also, to improve the reliability in this graph, a part of the seismic event history with no damage has been included in the graph. These events were between 2012 and 2013 with a significative magnitude ($M_{Richter}$>0.0). They were included because they represent cases where dynamic support was effective under dynamic loading. This kind of data was not considered by Heal et al. (2006).

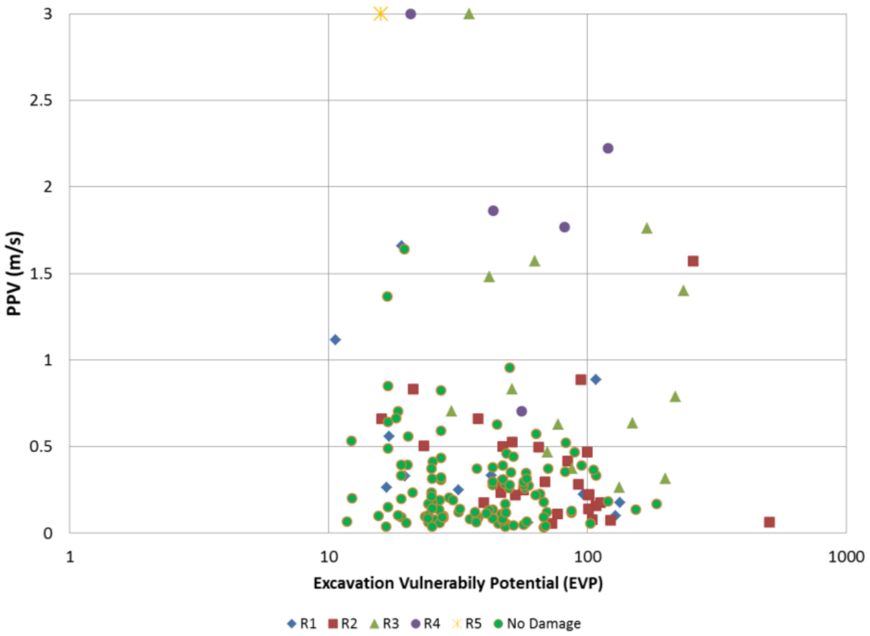

Figure 10 Laronde rockburst dataset of EVP versus ppv based on the equation of Heal et al. (2006)

Based on a review of the rockburst history at LaRonde, it was recognised that an important parameter was not considered by the EVP equation. It has been observed that the orientation of drifts relative to regional schistosity is involved in many cases of rockburst damage at Laronde. An additional parameter (E5) has been introduced to capture this effect. E5 helps to modify (reduce) the EVP by multiplying the end result. The equation that is proposed for LaRonde is:

$$EVP = \frac{E1}{E2} x \frac{\text{E3}}{E4} x\ E5 \tag{3}$$

It was established in Table 7 that drifts parallel to schistosity tend to exhibit a higher score on the RDS. With this observation, a drift perpendicular to the schistosity will have a smaller E5 value compared to a parallel drift (Table 8).

Table 8 Value for E5 factor

Drift orientation	E5 value
0-30°	1.5
30-60°	1.0
60-90°	0.5

A new graph was plotted with this new equation and proved to be more representative for LaRonde. The introduction of the E5 s factor results in a chart that is more representative of conditions at the mine (Figure 11).

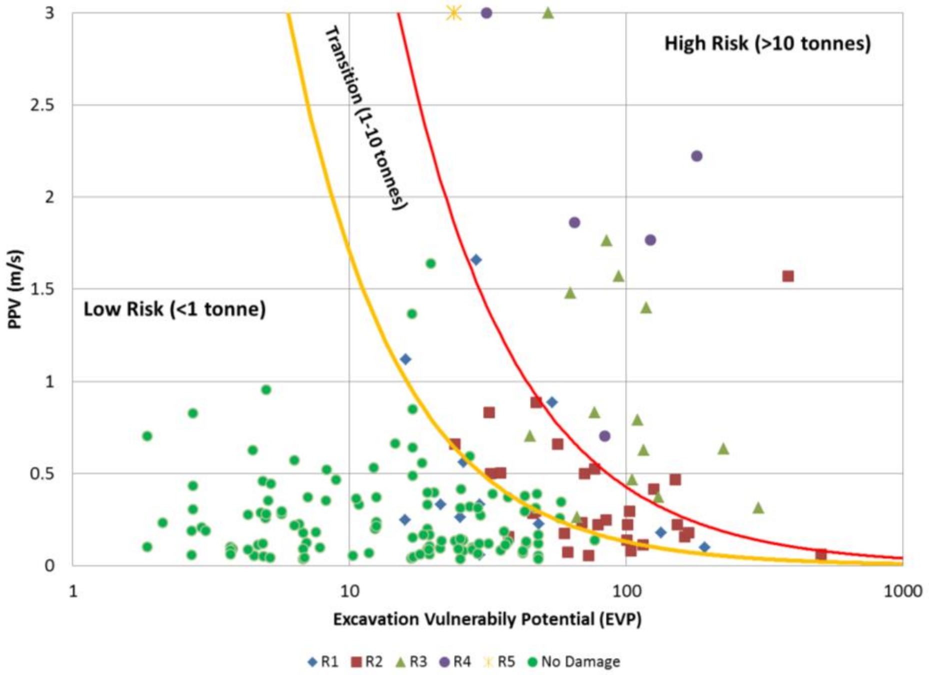

Figure 11 Ground support performance for LaRonde Mine with the modified equation

Three zones have been determined for the mine based on the rock displaced by a seismic event. A low risk event is considered to be one where a seismic event displaced less than 1 t and a high risk event is one where the event displaces more than 10 t. Between both zones, there is a transition zone where historic data shows that the quantity of displaced material is variable.

4 Anticipation of the ground support performance with mXrap

mXrap (Australian Centre for Geomechanics 2014) is software developed by the Australian Centre for Geomechanics, Agnico Eagle has been involved as a sponsor since 2004. The software groups events to improve data analysis. mXrap allows a seismic hazard to be estimated relative to ppv based on the seismic history of the mine with a probabilistic approach. This hazard is associated to a minode (or point) and is evaluated with the EVP parameters and the EVP equation which is already implemented in the software. By including the risk boundary in the previous graph (Figure 11) the software determines the ground support performance based on the LaRonde history and displays it with a colour code (Figure 12).

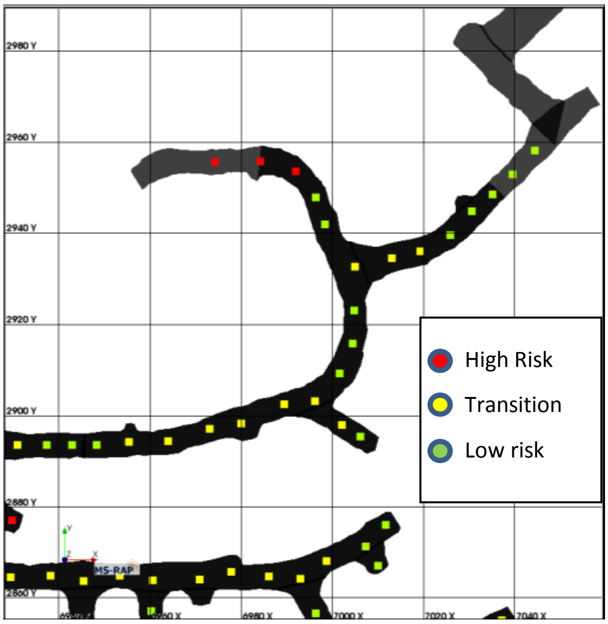

Figure 12 mXrap mapping for the ground support performance based on LaRonde data

This method is visual and rapidly evaluates the seismic risk of specific area at any time. If the seismic database in mXrap is kept up to date, it is possible to revise the ground support strategy following seismic activity in a specific area of the operation. A new ground support strategy can be evaluated by changing parameter E2 to determine if it satisfies the seismic conditions. As mining activities progress in time, the seismic hazard could change and affect the ppv evaluated by mXrap. This aspect must be taken into account during the analysis.

4.1 Case study – ramp access 252-257

An improvement of ground support in part of an access to a ramp was implemented after an investigation. Previously the area was supported with standard ground support; it was upgraded to dynamic support considering the increase in seismicity in the area. A couple of weeks following a seismic event of a 2.0 Richter magnitude was recorded 15 m from this access. In Figure 13, a small amount of damage (split set bolt broken and hybrid bolt taking load) with a small ejection of rock (<1 t) can be seen in the affected underground ramp access.

Figure 13 Small damage (R1) following seismic event M_{Richter} 2.0

The graph in Figure 14 shows the performance of ground support for this case study. The initial standard was in the high risk zone but with the implementation of the dynamic support, the point moves into the low risk zone. It is not necessarily clear that this change helped reduce the damage, but the graph helped to make a decision to improve ground support in this area. Following the mine history, the damage caused by this event was in agreement with the graph.

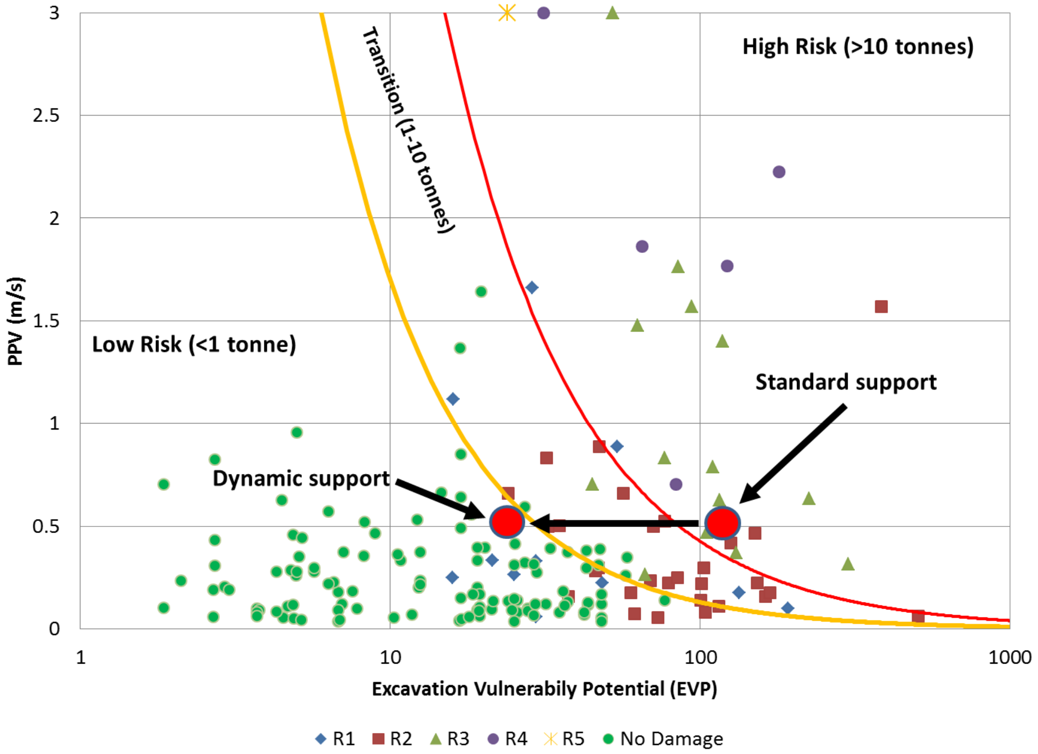

Figure 14 Performance of standard and dynamic ground support standards under the same circumstance

5 Conclusions

Seismicity at LaRonde continues to be a challenge to the operation. In the past squeezing was the main ground control issue, but now seismicity is becoming more important with the increase of the in situ stresses and rock mass strength. The review of the rockbursts at the LaRonde mine has helped to produce a practical tool used by the ground control group to evaluate and reduce seismic risk of underground excavations.

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