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Optimisation of the exclusion protocols following seismic events at the Goldex mine

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Abstract

The primary mining zone at the Goldex mine faces a relatively high seismic hazard for the depth of the deposit (≤ 1.2 km) due to its unique combination of 3D stoping geometry and geological and structural context. Seismic risk management practices at Goldex include exclusion protocols after production blasts, development blasts in high-seismic-hazard areas and major seismic events. This paper focuses on optimising exclusion protocol durations following major seismic events. These protocols aim to limit worker exposure to potentially damaging aftershocks. While extensive research has addressed exclusion protocols for production blasts and large-magnitude events, lower-magnitude events (MW0.5–2.0 range) have been comparatively overlooked. These smaller events, though less impactful, can still present hazards and significantly disrupt production. A comprehensive back-analysis of the response of these events at the Goldex mine was conducted and compared with the current protocols' duration. The optimisation resulted in a 50% reduction of re-entry times, thereby enhancing operational efficiency without increasing risks to worker safety. This paper details the methodology used for this review, the communication process with mine management and the health and safety committee, and the final decision-making process for implementing changes to the protocols.

Keywords: *seismic risk management, exclusion protocols, case study*

1 Introduction

Seismic risk management is critical in mining operations to ensure worker safety and maintain productivity. The Goldex mine presents a unique challenge due to its relatively high seismic hazard at a depth of ≤ 1.2 km. The combination of high intact rock properties, rock mass with sparse discontinuous jointing, large-scale fault-slip-prone structures, and a high extraction (void) ratio in the footwall where large infrastructures and main accesses are located, contributes to this hazard.

Current seismic risk management practices at Goldex include exclusion protocols following production blasts, development blasts in high-seismic-hazard areas and major seismic events (defined as events of moment magnitude [MW] ≥ 0.5). These protocols are crucial for protecting workers from potentially damaging seismic events. While extensive research has been conducted on exclusion protocols for production blasts and large-magnitude events, protocols for lower-magnitude events (MW0.5–2.0) have received less attention. Smaller events, though less impactful, occur more frequently and their exclusion protocols, though shorter, can cumulatively disrupt production significantly. The Goldex mine deposit's 3D geometry and the proximity of level accesses to the stoping areas reduce flexibility and magnify the impact of exclusion protocols of smaller-magnitude events on mine productivity.

This paper discusses optimisation of the durations of exclusion protocol following major seismic events to balance safety with productivity. The methodology involved a comprehensive back-analysis of seismic data, aiming to reduce re-entry times while maintaining safety standards. The optimisation process was presented to and discussed with mine management, leading to the adoption of refined protocols. This decision-making

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process, supported by a detailed review of seismic responses, highlights the importance of data-driven adjustments to enhance both safety and productivity in high-seismic-hazard mining environments.

2 Goldex mine background

The Goldex mine is an underground orogenic gold deposit owned and operated by Agnico Eagle Mines Limited (AEM). The mine is located at the western outskirts of the city of Val-d'Or, approximately 500 km northwest of Montreal and approximately 60 km east of AEM's LaRonde Complex. Mining at Goldex began in 2008, with operations in the current main mining zone (Deep 1) commencing in 2017. The history of mining activities prior to 2017 is detailed in works by Mercier-Langevin (2019) and Doucet et al. (2022). The Goldex mine is a low-grade, high-tonnage deposit, extracted at a rate of approximately 7,000 t/day. In 2023 it reported an average gold grade of 1.74 g/t, producing 140,983 ounces of gold (AEM 2023).

2.1 A seismic mine in town

The Goldex mine is approximately 4 km from Val-d'Or's downtown and less than 2 km from the nearest commercial area. In this context the vibrations caused by large-magnitude seismic events induced by mining at the Goldex mine are perceptible throughout the city and often raise concerns among residents. These events are frequently discussed on social media moments after they occur and are reported by local media outlets (Radio-Canada 2023).

In response, Goldex has developed a transparent, open and respectful approach to community relations, encapsulated in the *Good Neighbouring Guide*. This guide includes strategies for managing noise, dust, water sources and vibrations from production blasts and seismic events (AEM 2024).

2.2 Mining zones, geology settings and level layout

The Goldex deposit consists of mining zones in two distinct geological settings (Figure 1):

1. Goldex diorite mining zones including M zone (near surface), GEZ (inactive), E zone (inactive), Deep 1 zone (current main mining zone) and Deep 2 zone (started in June 2024). All of these zones are part of the same low-grade steeply north-northeast-dipping vein stockwork
2. south zones with higher-grade narrow veins and disseminated sulphides' zones located in the basaltic footwall host rocks of the Goldex diorite.

The active mining zones in the Goldex diorite are mined using a longhole sublevel primary-secondary open-stoping mining method, and stopes are primarily backfilled with cemented paste backfill. Each panel is multiple stopes thick (north–south). Stope dimensions are substantial, typically 50 m high, 22 m wide and 22 to 30 m long, and are generally sub-vertical. Conversely, the south zones consist of several individual lenses, generally of a single stope thickness, with smaller dimensions: 25–35 m high, 6–12 m wide and 10–20 m long. Some lenses are sub-vertical while others dip at 50–65°.

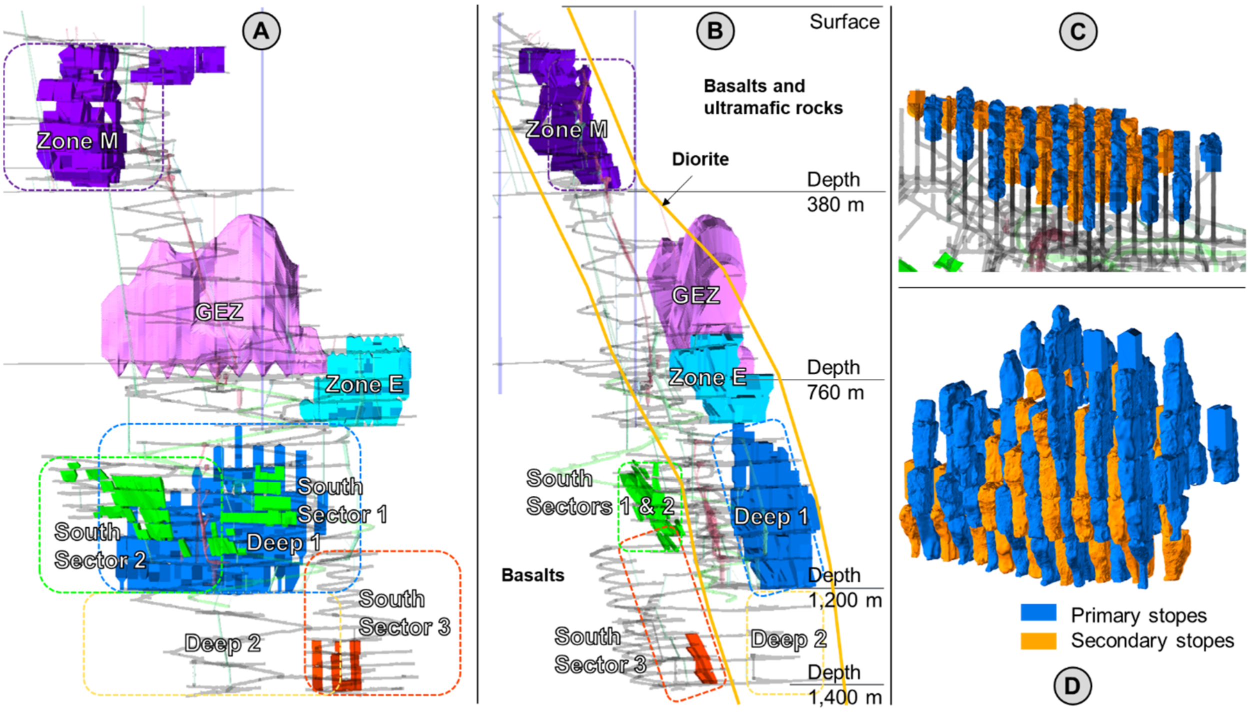


Figure 1 Mining zones at Goldex: (a) View looking north; (b) View looking west. Deep 1 zone primary and secondary panels: (c) Plan view; (d) Isometric view looking northwest. The approximate extent of the life-of-mine is shown by the dashed lines

The geological context, deformation history and rock properties of the Goldex mine are extensively described by Falmagne et al. (2024). For the purpose of this paper, the geological setting leading to high seismic hazard in the Deep 1 zone is summarised as follows:

- The Goldex diorite is a homogeneous, stiff (Young's modulus: 60–70 GPa), very strong (UCS: 175–250 MPa), brittle and mostly undeformed medium-grained intrusive rock unit with sparse discontinuous jointing, all of which contribute to its high energy storage capacity and high potential for dynamic rupture (Diederichs 2018).
- It has the presence of large-scale geological structures crosscutting the Goldex diorite in the mining area and the footwall abutment, including steeply dipping decametric to metric mylonitic ductile shear zones and brittle faults as well as decametric to metric sub-vertical diabase dykes in the western part of the Deep 1 zone.

The Goldex diorite is bordered by several-metre-wide zones of strongly sheared and altered basalts and komatiites transformed into chlorite-carbonate and talc-carbonate schists, respectively (Falmagne et al. 2024) and referred to as the north and south shears. When planning the layout of accesses and infrastructures in the Deep 1 zone it was not anticipated that such high seismic hazards would be present. Consequently excavations were strategically placed in the higher-quality Goldex diorite to avoid the lower-quality south shear, resulting in the proximity of the excavations to the mining area. Additionally, a limited understanding of the potential for future seismic hazards during the planning phase led to suboptimal decisions. These included an excessive number of excavations in the footwall, and the creation of numerous relatively small pillars which are just big enough to store energy and generate events but not crush. A typical level layout with infrastructures in the footwall is shown in Figure 2.

Figure 2 **Typical level layout in the Deep 1 zone**

2.3 Seismic activity overview

At the Goldex mine, seismic events of MW ≥ 0.5 are classified as major events and those with MW ≥ 2.0 as large events. Large events occur every three to six months, with the most significant event to date being of MW2.9.

Stope stability in Deep 1 is generally not a concern due to the high quality of the rock mass. Signs of high stress occasionally manifest as deformation in the V30 slot raises or minor spalling in stope accesses, yet significant stress fracturing or stope instability due to seismic activity is uncommon. The stress redistribution and new stress concentrations associated with the mining of a stope are not affecting the stope itself but are instead leading to seismic hazard in waste pillars in the stoping area and abutments, particularly the footwall abutment where large infrastructures and primary accesses are located. On several occasions large events that occurred in the upper levels of Deep 1 generated high-magnitude aftershocks around the large ore-handling infrastructure excavations located in the lower footwall abutment. Development headings in Deep 1 are typically developed in aseismic conditions but are later affected by seismicity when the stoping progresses.

The seismic history of Deep 1 can be broadly summarised into four distinct periods (Figures 3 and 4):

1. 2017 to mid-2020: initial phases of Deep 1, with primary panels advancing and relatively low seismic hazard. The major events were mainly localised in the mining area
2. mid-2020 to end-2021: the stoping sequence was not strictly adhered to, leading to primary panels being overly advanced relative to adjacent secondary panels. Additionally, a significant volume of waste rock (non-ore material) was present at L105 in the centre of the pyramid. By trying to maintain the overall pyramidal mining sequence in the centre of the zone, the sequence skips over L105, thereby creating a temporary internal sill pillar. This configuration resulted in a sharp increase in both the frequency and severity of seismic events. The major events were concentrated in the internal sill pillar area but also appeared deeper in the footwall abutment around Deep 1 large infrastructures
3. end-2021 to mid-2022: efforts focused on catching up with the mining of secondary stopes to regain control over seismicity. Concurrently, strategic measures were implemented to reduce stope voids and limit the simultaneous mining of stopes that had a high potential to generate large events (lead

stopes, stopes at the footwall abutment, stopes closing ‘stress windows’). The number of major events were significantly reduced but events are still occurring in the footwall abutment

4. mid-2022 to present: although strategic measures continue to mitigate seismic risks, the seismic hazard remains high in the now mature Deep 1 pyramid and is expected to persist. The major events occur mainly outside the mining area and deeper in the abutments.

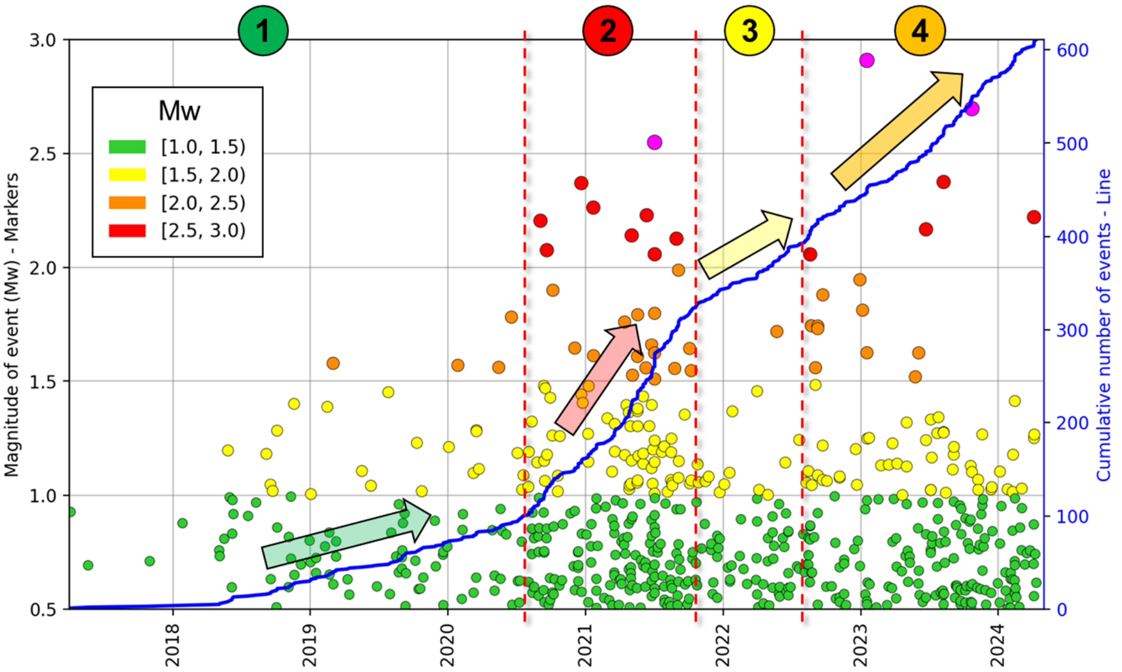


Figure 3 **Time-magnitude plot (events MW ≥ 0.5 only) showing the evolution of the seismicity in the Deep 1 zone since the start of mining in 2017**

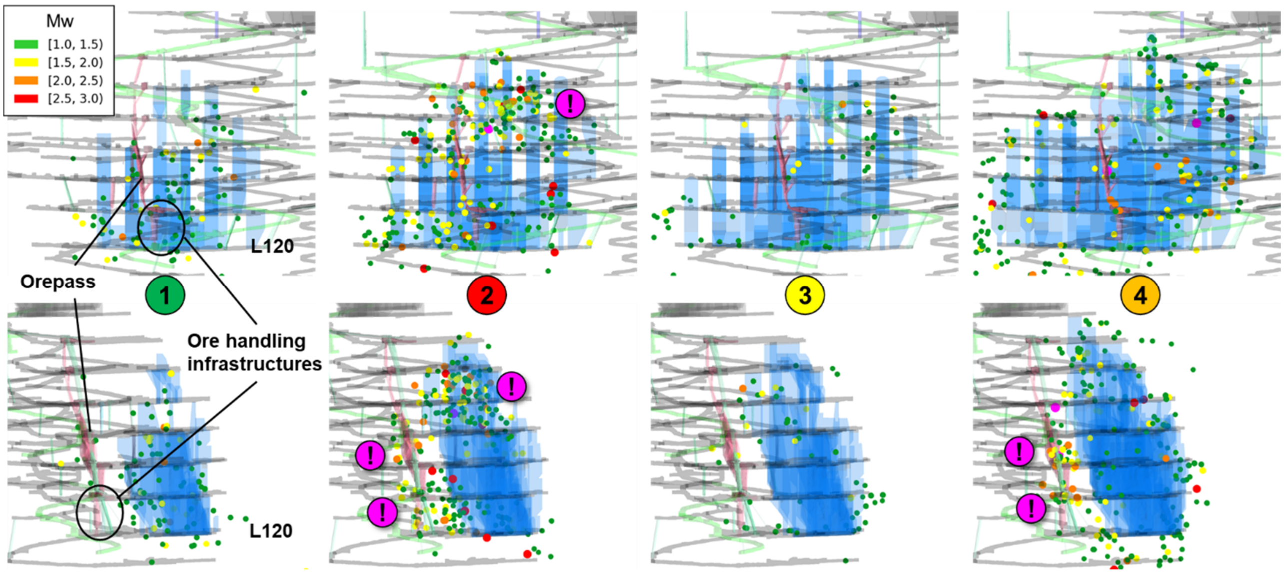


Figure 4 **Location of the seismic events for the four distinct seismicity periods identified in Figure 3. View looking north (top). View looking west (bottom). The purple exclamation mark circles show the areas with elevated frequency and severity of seismic events: around orepass and large ore-handling infrastructures for periods 2 and 4, and in the internal sill pillar in period 2**

In contrast, the south zones (sectors 1 and 2), despite being at similar elevations to Deep 1, are significantly different in terms of seismicity, with only one major event (MW ≥ 0.5) recorded since the start of the zone in

2019. The structural geology of the south zones is complex, including numerous ductile shear zones, however, the weaker rock mass, smaller stope dimensions, longitudinal mining approach and fewer excavations around the stoping area contribute to their lower seismic profile.

The analysis of seismicity in Deep 1 underscores that the zone's depth alone does not inherently predispose it to seismic activity. Although the characteristics of the Goldex diorite (massive, homogeneous, stiff, strong and brittle) and the presence of large geological structures naturally favour a seismic environment (Falmagne et al. 2024), the high-seismic-hazard conditions experienced would likely not have been as severe without the specific combination of large stopes, waste pillars to concentrate stresses, and numerous excavations and pillars in the immediate footwall abutment.

3 Seismic risk management at Goldex

In Canada's federal state system, occupational health and safety falls under provincial jurisdiction. Unlike Ontario, which implemented amendments in September 2023 to require underground mines to develop and maintain a seismic risk management program (SRMP), Québec's health and safety regulations for mines do not specifically address seismic risk management. However, recognising the importance of seismic risk management across its operations in multiple Canadian provinces, AEM has included an SRMP as part of the ground control management plan for all its seismic mines in Canada. The SRMP at Goldex generally follows the process outlined in the SRMP flow chart by the Australian Centre for Geomechanics (Potvin et al. 2023).

At Goldex, seismic hazard management tasks are primarily the responsibility of the ground control team, as is typical in many seismically active mines. The geology department also plays a critical role due to the significance of geological structures in understanding and managing seismic activity. Significant efforts are made to maintain an up-to-date and representative structural geology model. Furthermore, to allow the ground control team more time to focus on seismic hazard management, backfill planning is handled by the short-term planning department, an arrangement that has proven to be particularly effective.

Daily seismic hazard assessments are conducted to identify risks of strainbursting at development faces and to adjust production blast exclusion protocols. Long-term assessments are carried out periodically to review strategic control measures. A comprehensive mine-wide seismic hazard report is completed monthly and distributed to the engineering team, mine supervision and mine management. Mine-wide numerical modelling, using a strain softening dilatant explicit finite element model calibrated to seismicity (Dehkhoda et al. 2023), supports long-term mining scenario comparisons and forecasts for future hazards at a mining-zone scale. The results of the numerical modelling are also used in the forensic analysis of large events and rockbursts.

In terms of control measures, due to the 3D geometry and structural geology settings of the Deep 1 zone strategic measures (design of openings, mining sequence) cannot alone remove or reduce the risk to tolerable levels so tactical measures must be implemented. A dynamic ground support standard was developed and implemented in 2021. It is being installed retroactively in identified areas of high seismic hazard in Deep 1 and in all the developments of the new Deep 2 zone.

The principal tactical measure to reduce worker exposure to seismic hazards involves the use of exclusion (re-entry) protocols. At Goldex, two main types of protocols are employed:

1. planned exclusion protocols for production blasts, recently optimised using the modified Omori law (MOL) approach (Section 4.3).
2. triggered exclusion protocols put in place following a major seismic event (MW ≥ 0.5), which are the focus of this paper. These protocols aim to protect workers from exposure to high-magnitude, potentially damaging aftershock events.

Thirty minutes before the end of any exclusion protocol for production blasts or seismic events of MW ≥ 1.5, the decay and event rate are reviewed by the person on seismic guard (available 24/7). The protocol is extended if the event rate exceeds predefined thresholds. At the end of any exclusion protocol, closed workplaces are inspected by either a mine supervisor or ground control personnel.

Mine management is actively involved in seismic risk management, with risks communicated to them through mine daily meetings, weekly operational reports, monthly seismicity reports, monthly meetings focused on seismicity and ground control, and forensic analyses of large events and rockbursts. Senior AEM management is kept informed of seismic risks at Goldex through the geomechanical component of weekly and monthly operational reports and occasional meetings on geomechanical issues.

4 Back-analysis and optimisation of exclusion protocols following major events

4.1 Initial exclusion protocols

Fixed blanket-style exclusion protocols after major events were established early in the life of the Deep 1 zone. At that time, experience and history of seismic response were limited and the seismic system was still being deployed. Without sufficient reliable data and experience a conservative approach had to be taken. The exclusion protocols used for Deep 1 before the review are presented in Table 1.

The re-entry times presented in Table 1 increase almost linearly with increased magnitude and are capped at 12 hours for events MW ≥ 2, as shown in Figure 5. However, each whole number increase in magnitude represents a tenfold increase in measured amplitude and corresponds to roughly 32 times more energy release, as schematised in Figure 5. Therefore the probability that a trigger seismic event generates damaging aftershocks can be considered to increase logarithmically with increased magnitude value. This mismatch between the linear re-entry times and the logarithmic increase in probability of occurrence means the protocols are either too long for low-magnitude events or too short for larger-magnitude events. This observation became the basis of the back-analysis and optimisation work presented in this paper.

Table 1 Exclusion protocols following a major event (MW ≥ 0.5) in Deep 1 prior to review and optimisation

Magnitude of event (MW)	Duration of protocol (hours)	Spatial extent of protocol from seismic event location
0.5 ≤ MW ≤ 1.0	2	Close drawpoints each side at the level of the event and one level above and/or below. Close the footwall drive if the event is less than 30 m from it (east or west side of the central access).
1.0 ≤ MW ≤ 1.5	4	Close the sector (west or east) at the level of the event and one level above and/or below.
1.5 ≤ MW ≤ 2.0	8	Close the entire level at the elevation of the event, and one level above and below.
2.0 ≤ MW ≤ 2.5	12	Close the entire level at the elevation of the event, and two levels above and below. Close the Deep 1 ore-handling infrastructures (only remote operation is allowed). An inspection by the ground control team is mandatory before re-entry.
MW ≥ 2.5	12	Close Deep 1, Deep 2 and the south zones entirely. An inspection by the ground control team is mandatory before re-entry.

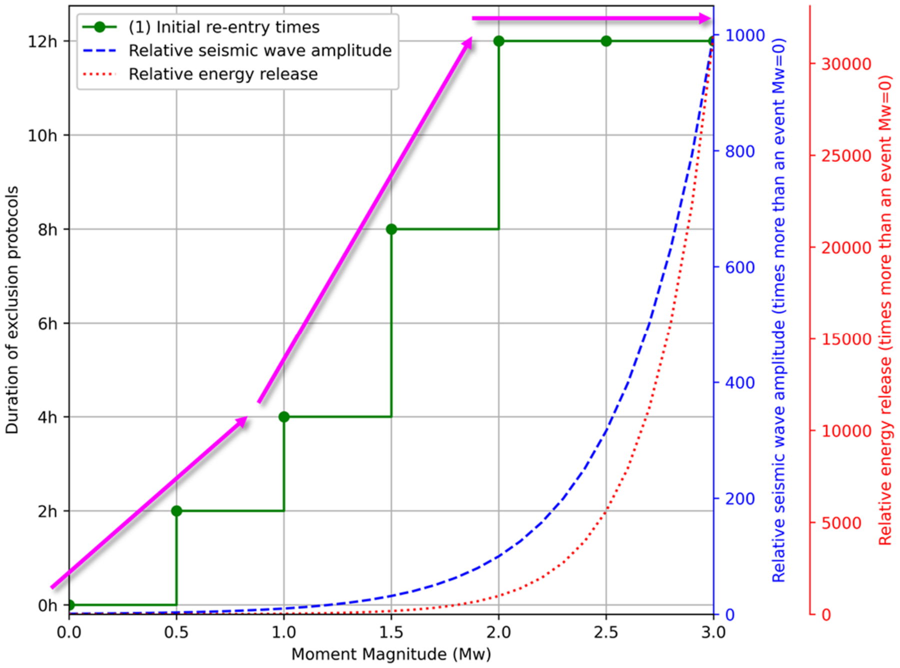


Figure 5 **Comparison of the increase of re-entry times (from Table 1) with the relative increase in released energy and seismic event amplitude for increasing magnitude. The linear increase of the re-entry times with increased magnitude is highlighted by the magenta arrows**

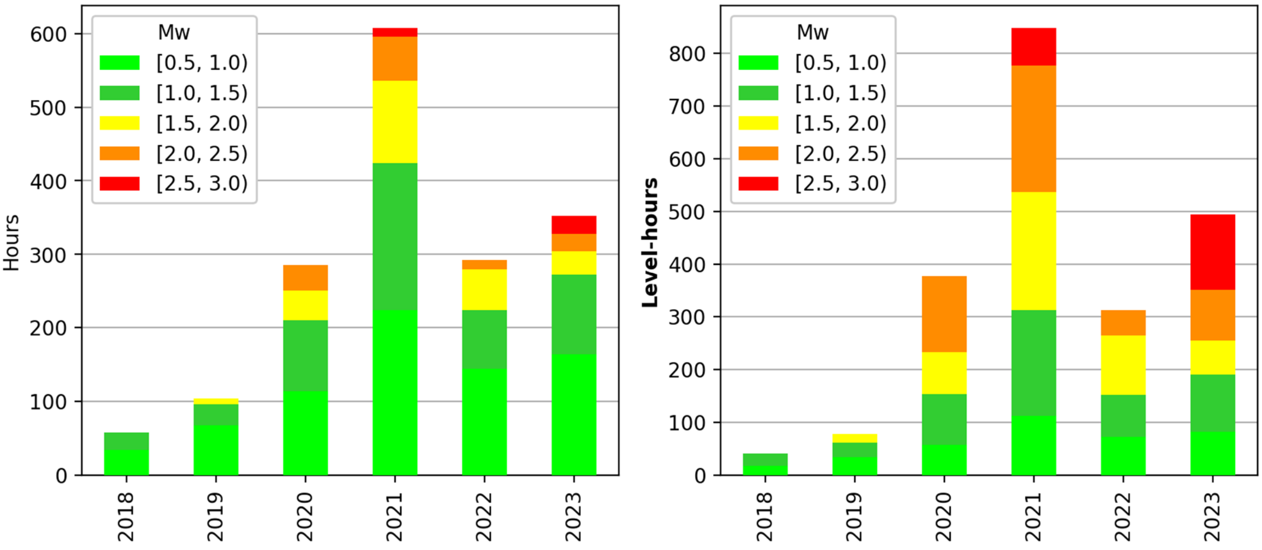
4.2 Discussion on the approach for back-analysis

The protocols include time (re-entry time) and spatial components. The review of seismic event locations and clustering is part of the daily routine seismicity analyses and is generally a straightforward process. The spatial component of the protocols was adjusted organically on several occasions since the start of the Deep 1 zone as: (1) experience was gained on the spatial extent of the seismic response of production blasts and large events, and (2) the seismic system improved in coverage, location accuracy and sensitivity with the addition of new sensors. The number of accelerometers in the Deep 1 zone increased from seven in 2020 to 23 in 2024, resulting in a decrease of M_{min} from –1.0 to –2.0 over this period, full coverage of the stoping area and footwall, and an accuracy in those areas now of 10 to 15 m.

Despite these improvements the potential optimisation of the duration of the initial blanket-style re-entry times was left unexplored. This optimisation aims to reduce the number of hours of exclusion as much as possible without significantly increasing the likelihood of exposure of the workers to a major aftershock. Even with sufficient data available the optimisation was not pursued due to the lack of a clear industry-acknowledged process for practitioners and the considerable effort anticipated in performing the necessary back-analysis.

Extensive research over the past 15 years focused on exclusion protocols following production blasts and large-magnitude events. Woodward & Wesselo (2015), Tierney & Morkel (2017) and Morkel & Rossi-Riviera (2017) can be cited among others who based their work on the MOL approach of Vallejos & McKinnon (2010). However, lower-magnitude major events, in the MW0.5–2.0 range, have been comparatively overlooked. While they do not generally have impactful consequences compared to larger events, these smaller events can still present a significant hazard to workers. As an example, the lowest-magnitude event that caused ejection of rock at Goldex (that we are aware of) is 0.8MW (rock ejected from the non-supported portion of the lower wall). Minor bulking/spalling and minor damage to the support is often observed in the 1.0–1.5 range and frequent in the MW1.5–2.0 range.

Smaller major events are significantly more frequent than large-magnitude events and the sum of their exclusion protocols, although shorter, disrupts production almost as much overall as large events. The 3D geometry of the Deep 1 zone and the relative proximity of the level accesses to the stoping area reduce flexibility and magnify the impact of exclusion protocols for smaller-magnitude events on mine productivity, as one small event can close access to multiple stopes at the same time. The impact of the smaller major events is illustrated in Figure 6. The left plot shows the sum of the re-entry times of the initial protocols (Table 1) for the major events in the database coloured by magnitude bins. However, as shown in Table 1, the spatial extent of the exclusion protocols increases with the magnitude, with the larger-magnitude events having a greater impact on production. To better account for the impact of the larger events, the re-entry times are expressed on the right plot as 'level-hours', which is defined as 'one complete Deep 1 level closed for one hour'.



(a) (b)

Figure 6 Sum of re-entry times of the initial protocols (Table 1) per year for the major events in the database, expressed as (a) hours and (b) level-hours. The bars are coloured for the magnitude of the events

The events in the MW0.5–2.0 range have a limited decay seismic response, which complicates the application of a MOL approach. For the back-analysis of those events it was first attempted to use the method proposed by Woodward & Wesselo (2015) to fit a MOL curve to each event and get an estimate of the *K*, *p* and *c* parameters (productivity, decay and time offset constants, respectively) and the associated Anderson-Darling statistic to build a response database. For most of the trigger events the number of aftershocks in the response was too low to establish all the parameters with confidence.

From there, different avenues were explored on how to perform efficiently the back-analysis of all the events in the database. The goal was to determine for each event the time to the 'end of the seismic response' that could then be compared to the initial blanket-style exclusion protocols. Potvin (2009) documents a practice commonly used in Western Australian mines where up to 90% of the cumulative energy dissipated is used as a re-entry rule. Potvin (2009) explains the rationale behind this practice:

'The underlying assumption is that once 90% of the total energy has been released, the rock mass can be considered to have readjusted to the new state of stress and is unlikely to produce a significant event'.

While the 90% rule is purely arbitrary it has the advantages of being intuitive and easy to implement for a back-analysis exercise. This simple approach was used as the first step in the back-analysis methodology presented in the next section.

4.3 Methodology

The back-analysis included all the events of magnitude MW ≥ 0.5 (major events) within the Deep 1 zone between the start of mining in 2017 to the end of 2023. A high-level review of the response of trigger events of magnitude 0.5 ≤ MW < 0.8 (for which damage was never observed) was performed and it was found that the response for those trigger events is insignificant to virtually none, so they were excluded from further analysis. This discarded about half of the total number of events in the major seismic events database.

The following methodology was applied for the back-analysis of trigger events of MW ≥ 0.8 to determine the time to the end of response:

- Events of MW ≥ –2.0 (lower limit of the seismic system accuracy) in a radius of 150 m around the trigger event location were considered as response events.
- A window of eight hours after the trigger event was considered for the response events. The time search window was cut before the next blast window (i.e. daily at 17:00).
- Events that occurred in the hour following a production blast were excluded from the analysis as their response can be hidden by the blast response. In any case, these events are covered by the exclusion protocol of the production blasts.

The following parameters were considered to establish the end of the response of the trigger event:

- when possible, the time of maximum curvature (TMC) was calculated from a MOL curve fitting. This was applicable mostly for the events MW ≥ 2.0 only
- the absence of events MW ≥ 0.5 in the response time search window
- the cumulative count of events curve and a histogram of the count of events per 0.5 hour bins
- time when the cumulative energy dissipated reaches 90% of the total response over the time search window as suggested by Potvin (2009)
- time when the cumulative count of events reaches 90% of the total response over the time search window
- time when the event rate falls below the allowable event rate of the production blast Omori database, which is defined by the 50th percentile line of the TMC chart
- the time to the end of response was rounded up to the nearest 0.25-hour increment.

Unfortunately the back-analysis process could not be fully automated and involved the manual review of individual trigger event plots to determine the end of response time. Therefore the back-analysis process includes a subjective component but it is considered that the end of response times selected are on the conservative side, principally because the decision is weighted towards the number of events. Examples for low-magnitude and large-magnitude events are shown in Figure 7.

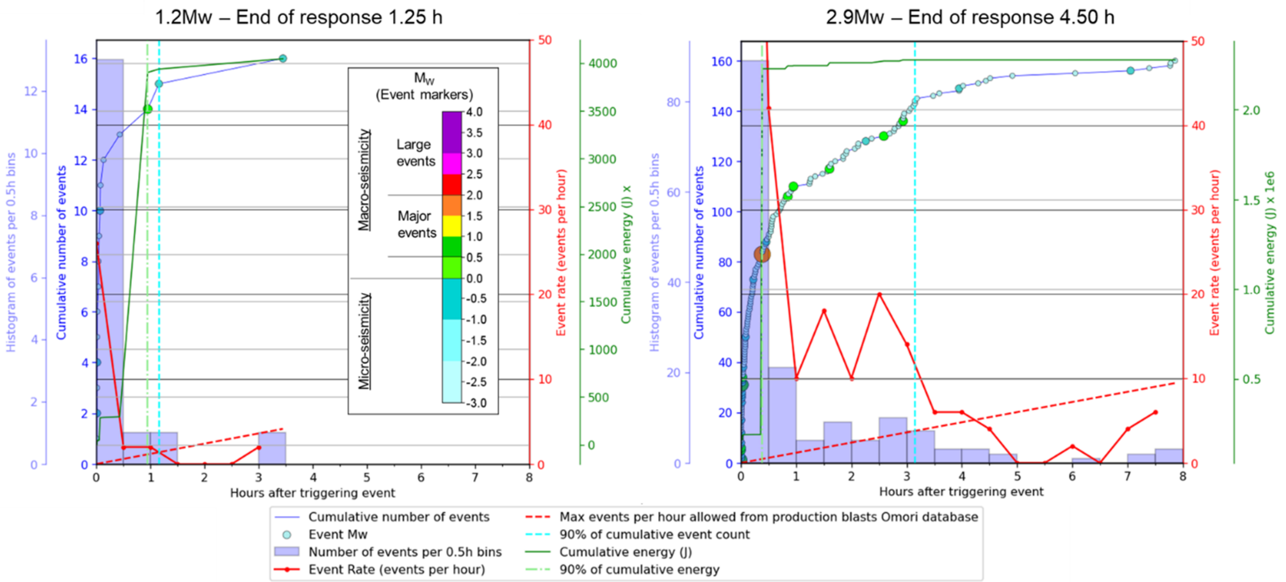


Figure 7 Typical response for a low-magnitude major event (left) and for a large-magnitude event (right)

4.4 Results and proposed optimisation

For most events the time required to reach the 90% cumulative count of events is significantly longer than the time needed to achieve the 90% cumulative energy release. As noted by Potvin (2009), focusing on the number of events can extend re-entry times because small- and large-magnitude events are weighted equally. However, the burden of proof is inherently higher when attempting to reduce mitigation measures compared to implementing them. Consequently, as an operator, it was deemed acceptable to consider the number of events in the decision-making process. Moreover, relying solely on cumulative energy release for a large event can be misleading if this event generates a major aftershock. In such cases the 90% threshold of the response is automatically reached when that major aftershock occurs. Given the brittle nature of the Goldex diorite, aftershocks with a magnitude of MW ≥ 0.8 occur shortly after the trigger events, typically within two hours of the trigger event. Therefore basing re-entry times solely on the 90% cumulative energy criterion would result in re-entry times being uniformly set at two hours.

The time for the end of the response of the MW ≥ 0.8 events are displayed as markers in Figure 8. The main finding of the back-analysis was that the initial protocols were consistently significantly longer than the trigger event conservative response time, with the difference gap increasing steeply with the increase in magnitude. Based on the back-analysis, the following modifications to the duration of the protocols were proposed:

- MW ≥ 2.5: the re-entry time was reduced to the longest response to date (six hours) plus a buffer of two hours, considering the higher risk associated with events of this magnitude.
- 1.5 ≤ MW < 2.5: the re-entry time was reduced to the longest response to date plus a buffer of one hour.
- 1.0 ≤ MW < 1.5: considering that events of this magnitude do not generally create aftershock events of MW ≥ 0.8, and thus do not present a hazard to workers past the initial trigger event, the re-entry time was reduced to the longest response to date (two hours).
- 0.8 ≤ MW < 1.0: exclusion protocols following events were abolished. This decision, based on the conservative approach detailed in Section 4.3, may seem contradictory since the events in this range do trigger a response. However, in the events' database, no MW < 1.0 events have produced an aftershock of MW ≥ 0.8. Considering that the purpose of exclusion protocols after major seismic events is to protect workers from potentially damaging aftershocks (i.e. MW ≥ 0.8), the decision to remove protocols for this magnitude range is justified. Operationally the minimum feasible protocol

duration is two hours, which accounts for the time it takes the mine supervisor to physically secure and then reopen the workplaces. Therefore the choices were limited to either zero hours or two hours.

- 0.5 ≤ MW < 0.8: as mentioned in Section 4.3, MW < 0.8 events have virtually no seismic response so their protocols were also abolished.

Except for the events MW < 1.0 discussed, the proposed re-entry times would have been longer than the response time of the totality of the events in the database used for the back-analysis.

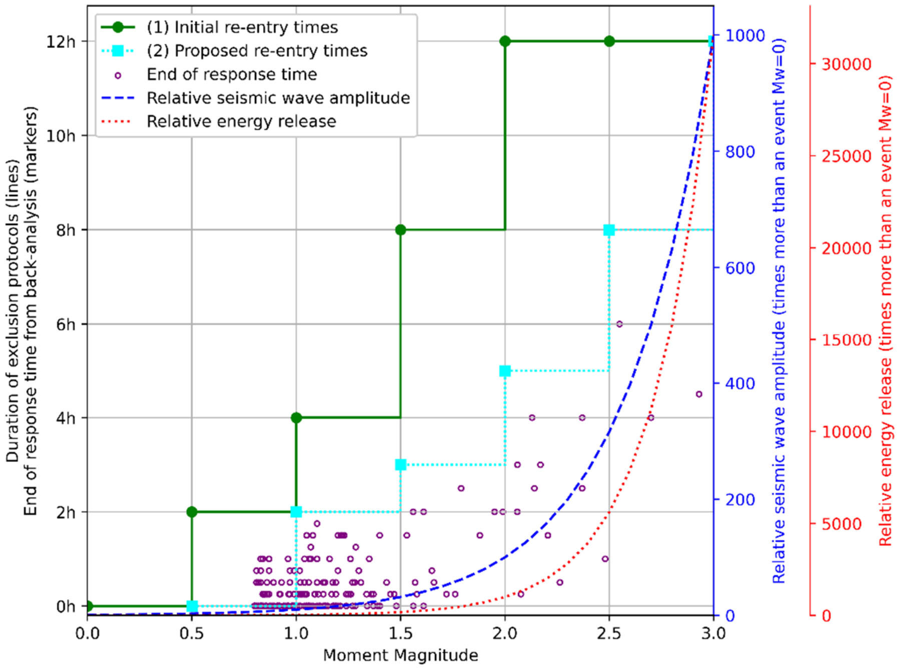


Figure 8 **Initial and proposed re-entry times based on the results of the back-analysis. The end of response time determined during the back-analysis are plotted as markers**

5 Decision-making process

Although the ground control team primarily handles seismic hazard management tasks, decisions regarding what constitutes acceptable or tolerable risks are made at the corporate level or by the mine management. As Hadjigeorgiou (2019) rightly points out:

> *'[…], it is not up to the ground control or rock mechanics engineer to establish a mine's risk appetite on geomechanical issues such as managing seismicity and meeting production requirements in a deep and high-stress mine'.*

Following this logic, major changes to seismic risk management procedures are presented by the ground control team to the mine management and discussed during monthly meetings focused on seismicity and ground control. For the exclusion protocols following major events, the proposed protocols (Section 4.4) were presented, as well as the potential productivity gains (see Section 6). The conclusion of the discussion was that the tolerable risk was lower for larger-magnitude events so the protocol durations for events MW ≥ 1.5 were increased compared to what the back-analysis suggests as being appropriate, i.e. in the interest of safety it was decided to be conservative for the larger seismic events. The comparison between the initial, proposed (based on back-analysis results) and adopted exclusion protocols are shown in Figure 9 and the difference with the initial protocols is presented in Table 2. The process described in this paper and the adopted protocol changes were documented in an internal document communicated to mine supervisors through face-to-face meetings, and was submitted to the joint health and safety committee for final approval. Following this approval, the procedure following a major seismic event was modified and the changes were communicated to the stakeholders.

It should be reiterated that the decay and seismic event rates are reviewed by the person on seismic guard 30 minutes before the end of exclusion protocol for events of MW ≥ 1.5. This review ensures that if a protocol happens to be too short it will be caught and extended. With this fail-safe in place the reduction in the duration of the protocols is achieved without introducing any significant additional risk to the workers.

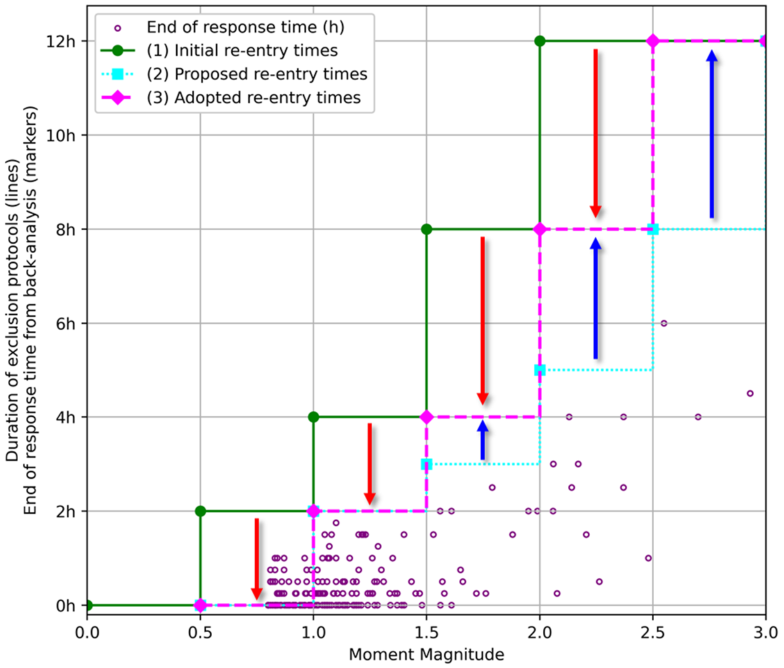


Figure 9 Comparison of the duration of the initial, proposed (based on back-analysis results) and adopted exclusion protocols. The end of response times determined during the back-analysis are plotted as markers. The arrows show the difference between the adopted, initial (red arrows) and proposed (blue arrows) protocols

Table 2 Comparison of the duration of the initial, proposed (based on back-analysis results) and adopted exclusion protocols. Comparison to the initial protocols is in brackets

Magnitude of event (MW)	Initial protocol (hours)	Proposed protocol (hours)	Adopted protocol (hours)
0.5 ≤ MW ≤ 1.0	2	0 (−2)	0 (−2)
1.0 ≤ MW ≤ 1.5	4	2 (−2)	2 (−2)
1.5 ≤ MW ≤ 2.0	8	3 (−5)	4 (−4)
2.0 ≤ MW ≤ 2.5	12	5 (−7)	8 (−4)
MW ≥ 2.5	12	8 (−4)	12 (0)

6 Productivity gains

As discussed in Section 5, the potential future productivity gains were considered in the decision process. These were established by calculating, for every previous seismic event used for the back-analysis, the difference between the initial protocol (applied at the time) and the newly adopted protocol.

Figure 10 shows annual productivity gains coloured for the magnitude of the events. The productivity gains are expressed in terms of level-hours, introduced in Section 4.2. Based on recent years the anticipated productivity gains could amount to approximately 200 level-hours: a substantial improvement in operational efficiency achieved without increasing risks to worker safety. Comparing Figure 6 with Figure 10 reveals that the productivity gains represent roughly half the re-entry times previously required for major seismic events in the database.

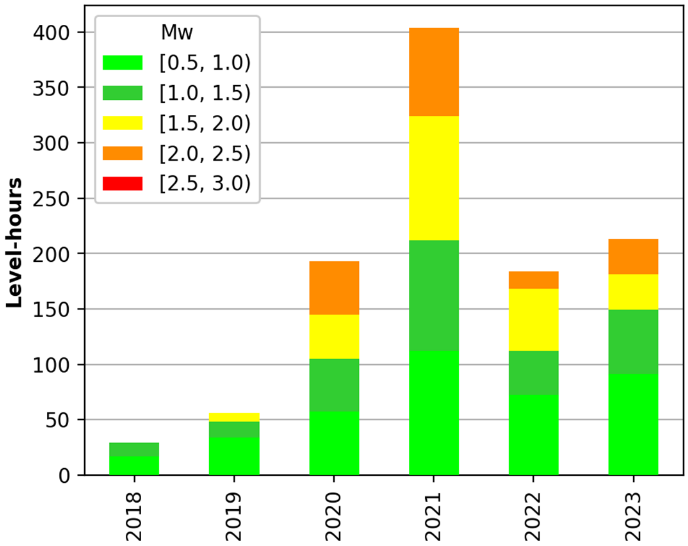


Figure 10 Potential productivity gains (measured in level-hours) calculated for the previous major seismic events. The bars are coloured for the magnitude of the events

7 Conclusion

The back-analysis presented in this paper underscores the importance of reassessing established procedures, particularly blanket rules, by examining the reasons and contexts for their implementation. As soon as sufficient data and field experience are available, the replacement of blanket rules by data-driven decisions and procedures should always be considered. Data-driven procedures should also be re-evaluated on a periodic basis as mining environments are dynamic and evolve with time. Such reassessments often reveal opportunities for productivity gains that might be obscured by longstanding practices. Specifically, in the context of exclusion protocols following major seismic events, significant improvements in productivity can be achieved without increasing risks to workers. This becomes feasible once: (1) the seismic monitoring system is fully deployed, ensuring comprehensive coverage and reliability, and (2) sufficient experience and understanding of the seismic responses are acquired. Challenging the existing practices under these favourable conditions can uncover substantial benefits. Presenting comprehensive data and analyses to mine management enables informed decision-making that integrates health and safety considerations with production and financial objectives, ensuring that every decision enhances both worker safety and operational efficiency.

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References

Agnico Eagle Mines Limited 2023, *2023 Annual Report*, https://s21.q4cdn.com/374334112/files/doc_financials/annual/2023/Annual-Report-2023.pdf

Agnico Eagle Mines Limited 2024, https://abitibi.agnicoeagle.com/goldex/goldex-cadre-de-bon-voisinage/, viewed 5 May 2024

Dehkhoda, S, Beck, D & Levkovitch, V 2023, ‘Numerically simulated rate of energy release and its correlation with measured seismic potency’, paper presented at the 15th ISRM Congress, Salzburg, Austria, October 2023.

Diederichs, MS 2018, ‘Early assessment of dynamic rupture hazard for rockburst risk management in deep tunnel projects’, *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, no. 3, pp. 193–204, https://dx.doi.org/10.17159/2411-9717/2018/v118n3a1

Doucet, I, Côté, T, Falmagne, V 2022, ‘Managing the development of secondary drawpoints in high stress areas at Goldex Mine’, *RaSiM10: Proceedings of the Tenth International Conference on Rockbursts and Seismicity in Mines, Society for Mining*, Metallurgy and Exploration, Englewood.

Falmagne, V, Doucet, C, Yergeau, D, St-Onge, N, Durham, C, Jacobs, R, Pyy, A, Heller, A 2024, ‘Seismic response of large-scale geological structures in deep mines’, in P Andrieux & D Cumming-Potvin (eds), *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 153–170.

Hadjigeorgiou, J 2019, ‘Understanding, managing and communicating geomechanical mining risk’, in J Wesseloo (ed.), *MGR 2019: Proceedings of the First International Conference on Mining Geomechanical Risk*, Australian Centre for Geomechanics, Perth, pp. 3–20, https://doi.org/10.36487/ACG_rep/1905_0.1_Hadjigeorgiou

Mercier-Langevin, F 2019, ‘Ground support: a mine manager’s perspective’, in J Hadjigeorgiou & M Hudyma (eds), *Ground Support 2019: Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 29–40, https://doi.org/10.36487/ACG_rep/1925_0.03_Mercier-Langevin

Morkel, IG & Rossi-Rivera, P 2017, ‘The implementation and quantification of the Vallejos and McKinnon re-entry methodology’, in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 173–181, https://doi.org/10.36487/ACG_rep/1704_10_Morkel

Potvin, Y 2009, ‘Strategies and tactics to control seismic risks in mines’, *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 109, no. 3.

Potvin, Y, Wesseloo, J, Woodward, K, Morkel, IG, Tierney, S 2023, *Seismic Risk Management Practices in Underground Mines*, https://acg.uwa.edu.au/srmp

Radio-Canada 2023, https://ici.radio-canada.ca/nouvelle/1948863/magnitude-tremblement-terre-abitibi, viewed 28 June 2024.

Tierney, SR & Morkel, IG 2017, ‘The optimisation and comparison of re-entry assessment methodologies for use in seismically active mines’, in J Wesseloo (ed.), D*eep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 183–196, https://doi.org/10.36487/ACG_rep/1704_11_Tierney

Vallejos, JA & McKinnon, SD 2010, ‘Temporal evolution of aftershock sequences for re-entry protocol development in seismically active mines’, in M Van Sint Jan & Y Potvin (eds), *Deep Mining 2010: Proceedings of the Fifth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 199–214, https://doi.org/10.36487/ACG_repo/1074_14

Woodward, K & Wesseloo, J 2015, ‘Observed spatial and temporal behaviour of seismic rock mass response to blasting’, *The Journal of the Southern African Institute of Mining and Metallurgy*, vol. 115, no. 11, pp. 1044–1056.