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Delineation of hazard-based design events for dynamic support system analysis

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Abstract

The objective of a dynamic ground support system is to manage excavation damage associated with rockburst events. To achieve this objective, a dynamic support system must be engineered to withstand the unique loading conditions imparted in a high-stress, burst-prone environment. The process of defining those unique loading conditions focuses on identifying the expected failure mechanisms and estimating the expected damage intensity and failure severity to quantify the load demand that may be imparted onto the support system. Identification of the maximum probable 'design event' is a critical input parameter for support demand assessments in dynamic ground support system design. Defining dynamic loading conditions unique to probable 'design events' requires detailed seismic data analyses. Using a case study from a deep Canadian mine, seismic data analyses are engaged to identify impacting seismic response parameters, which are then applied to seismic domain delineation. Frequency–magnitude trends (and associated b-value analyses) are then evaluated in domained areas to define the 'design events'. Categorisation of the seismic hazard classes relies on the explicit 'design events' which deliver support demand input values necessary for optimising dynamic ground support design. Site-specific seismic data analyses deliver optimum load demand parameters appropriate for achieving an engineered dynamic ground support system design, effectively managing seismic hazard in a safe and economical manner.

Keywords: *seismicity, dynamic support, design event, hazard-based design*

1 Introduction

Seismicity is a widely recognised hazard in deep mining which is associated with seismogenic energy release during brittle fracture initiation and propagation in rock failure process. In mining, seismicity is induced by the redistribution of stress and strain as excavations are created. It can manifest as violent or dynamic failure of a volume of rock around the excavations that may be self-triggered, and/or triggered by a seismic strain wave transferred to the rock mass from more distant seismic sources such as structural slip mechanisms (Kaiser & Moss 2022). Managing rockbursting conditions in mine development and production environments is a complex and difficult challenge and requires the use of advanced analyses to develop engineering and operational controls appropriate for specific failure processes and excavation damage potential. While risk mitigation measures should include strategic (such as sequencing) and tactical (such as re-entry delays and exclusion zones, equipment selection and destressing) approaches, dynamic ground support would be the last line of defence for deep mines under dynamic loading conditions.

The objective of a dynamic ground support system is to manage excavation damage associated with rockburst events. To achieve this objective, the system must be engineered to control rock mass dilation and maintain confinement around the reinforcement elements. Furthermore, it should be capable of absorbing the kinetic energy released through the process of brittle damage and dynamic deformations. Good connectivity and load transfer between the surface support and reinforcement elements are additional key components for the system to be successful (Morissette & Hadjigeorgiou 2019). The process of defining those unique loading conditions focuses on identifying the expected failure mechanisms and estimating the expected damage intensity and failure severity to quantify the load demand that may be imparted onto the support system. Identification of the maximum probable 'design event' is a critical input parameter for support demand assessments in dynamic ground support system design. Defining dynamic loading conditions unique to probable 'design event' requires detailed seismic data analyses (Butler & Simser 2016).

In deep mining, sophisticated seismic monitoring systems are routinely used to monitor ground reaction. Where good quality seismic data is available, it is arguably one of the most valuable tools for understanding the full four-dimensional extent of where and when a rock mass or structure is transitioning through the yielding process, and characterises the energy released during fracturing and deformation (Wesseloo 2018). A critical step to strategic ground support design is to conduct a detailed review of seismic data to develop interpretations of the spatial and temporal distributions of seismogenic behaviour. This is a key part of the ground behaviour model and often involves seismic domaining. Comprehensive understanding of seismic ground response and hazard domains facilitates evidence-based design of dynamic ground support classes in different hazard levels.

Dynamic ground support design is conducted for a deep Canadian mine where seismic domain delineation and event sizing for each domain is first completed using seismic database, followed by a support design study for the derived hazard domains. The study is divided into two parts; the first part covered in this paper includes details seismic data analyses to identify impacting seismic response parameters, which are then applied to mine-wide seismic domain delineation. The application of hazard-based event sizing on dynamic ground support design is then described in second paper by Kalenchuk et al. (2023). Complementary to seismic data analyses in this paper, unusual occurrence (UO) records have been reviewed in detail with the objective of identifying causal factors contributing to each incident for interpreting the probable nature of the occurrence. Throughout the review, influencing parameters and the nature of in situ ground reaction were correlated with seismic response to characterise the nature of dynamic instability. The spatial delineation of the seismic domains is then achieved based on a general understanding of influencing parameters (identified by analyses of UOs and mine-wide seismic data), with refinement of spatial hazard at the local-scale according to proximity with conditions susceptible to the influencing parameters. Maximum probable design events are explicitly defined for domained areas using frequency–magnitude trends which provide key input values for dynamic ground support design evaluations.

2 Case study background

The case study investigated in this paper is a gold mine complex in Canada which currently operates at approximately 1,000 m below surface and is planned to extend to 1,500 m depth in future life of mine. A layout of the mine plan is shown in Figure 1. The mining plan primarily uses a longitudinal longhole stoping with retreat typically towards central level accesses, thereby creating diminishing central access pillars. Active development and production are progressing in four mining horizons, with a bottom-up sequencing in each horizon. Sill pillars are established between each of the mining horizons and are recovered by uphole stoping leaving small rib and skin pillars in place. Additionally, barren pillars are created locally in the plane of the ore where unmineralised areas (such as dykes) or uneconomical regions exist.

The orebody is hosted in a sequence of felsic to intermediate tuffs and volcanic rocks cross-cut by mafic dykes. Two regional vertical diabase dykes with typical widths of 20 m (but can be locally wider) crosscut the orebody. Horizons of flat-lying dykes are also found in various areas of the mine, as shown in Figure 1, with particular exposures at 785–820 m, and 940 m depths from surface. Another set of vertical dykes, typically subparallel to the orebody lenses, is also exposed in the mining area. The horizontal and ore-parallel vertical dykes are thin with typical widths of a few metres or less.

The host rock units have very similar average intact material strength, while the diabase dykes are found to be much stronger. Negligible variability is also observed spatially in host rock mass quality based on the geotechnical rock mass characterisation, while localised zones of poor rock mass quality at the dyke contacts are encountered. Typical rock mass quality in host rock is assigned a Q' range of 16–24 equivalent to 69 < GSI < 73 (empirically estimated from Q' based on Hoek et al. 1995), and in the regional diabase dykes are assigned a Q' range of 25–50 equivalent to 73 < GSI < 79.

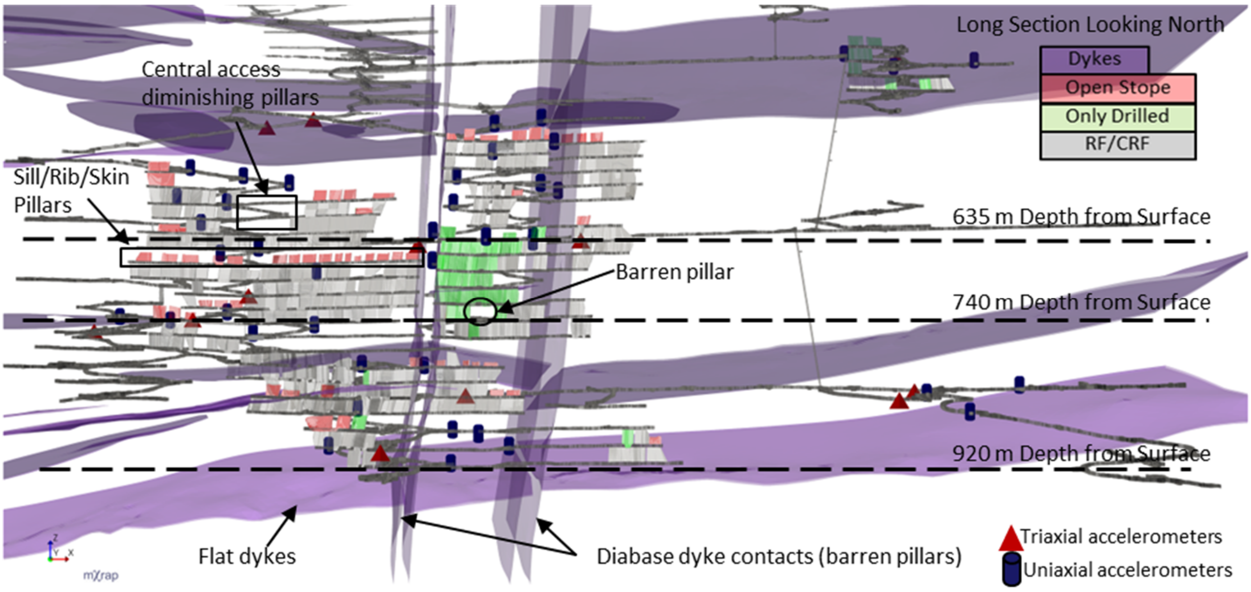


Figure 1 Mine configuration in long section, seismic array, overview of dykes and examples of pillar types

3 Historical review of seismicity and unusual occurrences

An engineered approach to the design of a dynamic ground support system requires an understanding of the expected rock mass response to potential loading conditions. Review of historical ground responses, UOs and seismicity offers insight into the rock mass failure processes and how rock failure can manifest as excavation damage which is intended to be controlled by ground support systems. In this study, a detailed review of the UOs and historical seismic data has been completed to characterise seismogenic ground response, with particular focus on establishing the maximum probably event magnitudes for domained conditions in order to define appropriate design events for the dynamic support evaluations.

3.1 Seismic monitoring setup and analysis

Seismicity is detected and measured through an underground array of 12 triaxial accelerometers and 42 uniaxial accelerometers, as shown in Figure 1. Complementary to the underground array of accelerometers is a strong ground motion sensor located on surface dedicated to the measurement of larger magnitude, lower frequency seismic events to compensate for the low frequency limitation of the underground accelerometer array, which limits the ability of the underground array to measure source parameters of large seismic events. A total of 102,290 seismic events have been recorded between February 2018 and July 2022. The mine maintains and uses the Australian Centre for Geomechanics (ACG) mXrap software (Harris & Wesseloo 2015) application for seismic data analyses.

3.1.1 General seismic response trends

A magnitude–time history chart of all seismic events is shown in Figure 2a. Focusing on large magnitude seismicity, a magnitude–time history plot of the filtered seismic population (magnitude > M_L0.5) is also included in Figure 2b. The typical daily event rate is plotted on the magnitude–time history plot as a 30-day moving average. A 30-day moving average trendline of large magnitude seismicity (plotted on Figure 2b with a dashed black line) demonstrates two short-term event rate increases. The first event rate increase is from October 2019 to December 2019, which coincides with the date/time recordings of the two largest events in the seismic database. During this time period, mining was actively advancing through the central diminishing pillars within a mining block between 635 and 740 m below surface, including recovery of a sill pillar in 655 m below surface. The second event rate increase was recorded in January 2022, which temporally coincides with the mining front advance 800 m below surface and within the central access pillar. Event rate increases depicted in the large magnitude seismicity trends confirm that mine design geometry, specifically diminishing and central pillar conditions in the specific mining method presented in this paper, are one of the primary influencing parameters of seismogenic rock mass response.

To further characterise local-scale seismic response over the monitoring period, the mining area is divided into spatial mining zones and mining horizons, as indicated in Figure 3. Cumulative event rate for each mining block is plotted in Figure 3. Comparatively, Block-B and Block-C are the most seismically active domains over the monitoring period. This trend is associated with the extraction ratios which are the highest in these two domains. To exclude the impact of extraction ratio (whereby seismic event rates generally increase with progressive stope extraction), the seismic event counts in each mining block have been normalised by the extraction volume (note: data analyses throughout this study include all seismic data since no overarching change in seismic trends were influenced by specific data filtering for system sensitivity). Figure 3 provides a graphical representation of the normalised seismic event count (inset table listing the number of events and the total excavation volumes), arranged from the shallowest zones to the deepest zones. The following observations are made:

- Seismic response generally increases with mining depth, independent of other parameter assessments (detailed in later sections). Figure 3 shows that the highest normalised seismic event rate coincides with the deepest mining zone (below 880 m depth in Block-G), despite its relatively low extraction ratio.
- Elevated seismic response recorded in Block-B is associated with active mining from the sill pillar at 655 m depth.
- Seismic activity is comparatively higher in Block-C versus Block-F, at similar depths. This is attributed to the retreat direction in Block-C which is from the abutments towards the central level accesses (creating diminishing pillars which would experience significant stress concentration). In contrast, Block-F stope sequencing has advanced in one direction, between the barren vertical dykes, and is associated with a lower level of seismicity for a comparatively similar depth.

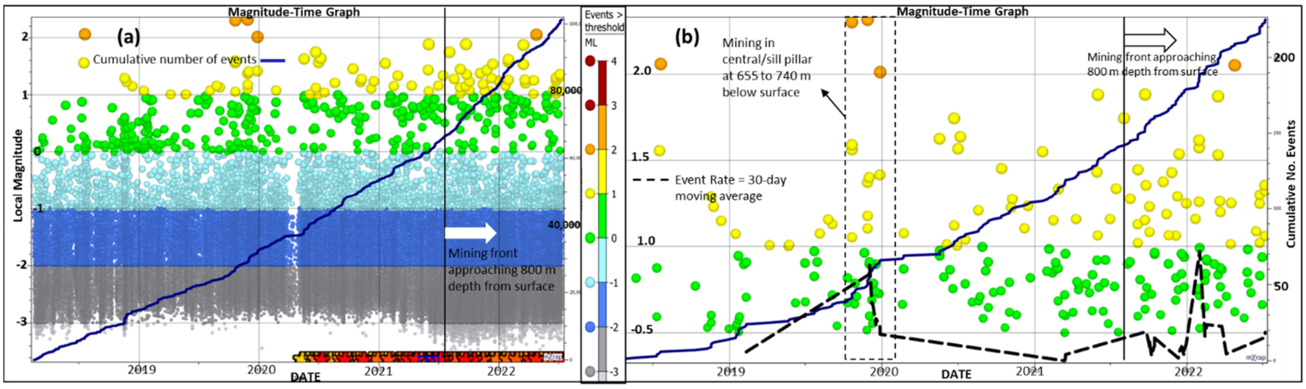
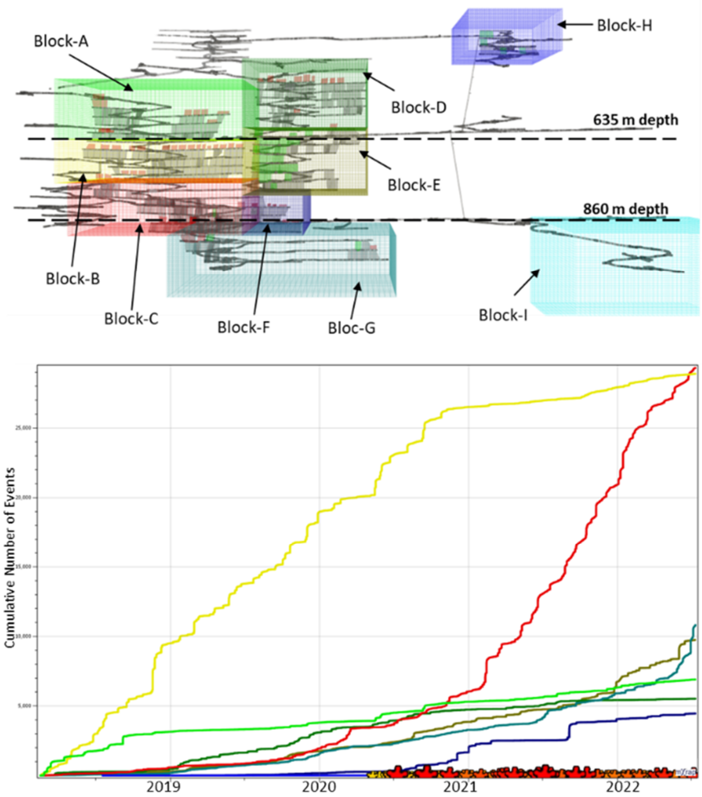
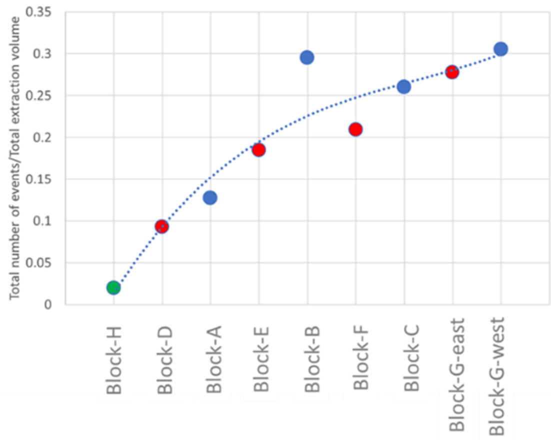


Figure 2 Magnitude–time graph with (a) cumulative number of events and (b) daily event rate plots



Mining Zone	Total Number of Events	Total Extraction Volume (m3)
Block-H	220	11179
Block-D	5518	59398
Block-A	6906	54248
Block-E	9746	52740
Block-B	28892	98010
Block-F	4457	21322
Block-C	29313	112631
Block-G-east	2277	8206
Block-west	8540	27990



(a) (b)

Figure 3 (a) Cumulative number of events in each mining block; (b) Normalised event rate trend within spatial mining zones

A spatial overview of large events (>M_L1.0) is shown in Figure 4 and the following observations are noted:

- The largest magnitude seismic events are M_L2.3, spatially coinciding within sill pillars.
- In total, 84 large events have been recorded over the seismic monitoring period, with spatial correlations as follows:
  - 37/84 large events occur within sill pillars.
  - 11/84 large events occur within 25 m of the regional diabase dykes.
  - 20/84 large events occur within 20 m of the sub-horizontal dykes.
  - 37/84 large events occur within 20 m of the ore-parallel dykes.
- 13/84 events occur in the footwall (FW) near level access drives and ramps.
- Production blast information in mXrap project is available only after May 2020; 60 of the large events have occurred since then. A short-term blast response analysis has been conducted for this time period to distinguish apparent blast-induced large events (defined as seismic event within 24 hours of a mine blast and within 50 m from blast location) from the apparent triggered events (defined as events after 24 hours of any mine blast).
  - Blast-induced events (15/60):
    - 15 of the large events occurred within 24 hours following a mine blast and within 50 m of known blast locations (an overview is shown in Figure 5a).

        - 14/15 of the blast-induced large events occur in proximity of the sill drives, while 1/14 events occurred near FW development (in 860 m depth access drive, as depicted in Figure 5a).
        - All the blast-induced events spatially coincide with dykes, sill pillars or central diminishing pillars.
    - Triggered events (45/60):
        - 45 of the large events are not well correlated temporally and/or spatially with production blasting. A spatial overview of the events is shown in Figure 5b.
        - 34/45 large, triggered events occur in proximity to ore sill drives while 11/45 events occur in the FW near ramp or level access development.
        - All of these large events are spatially coincident with the sill pillars, barren pillars, central diminishing pillars, and/or dykes.

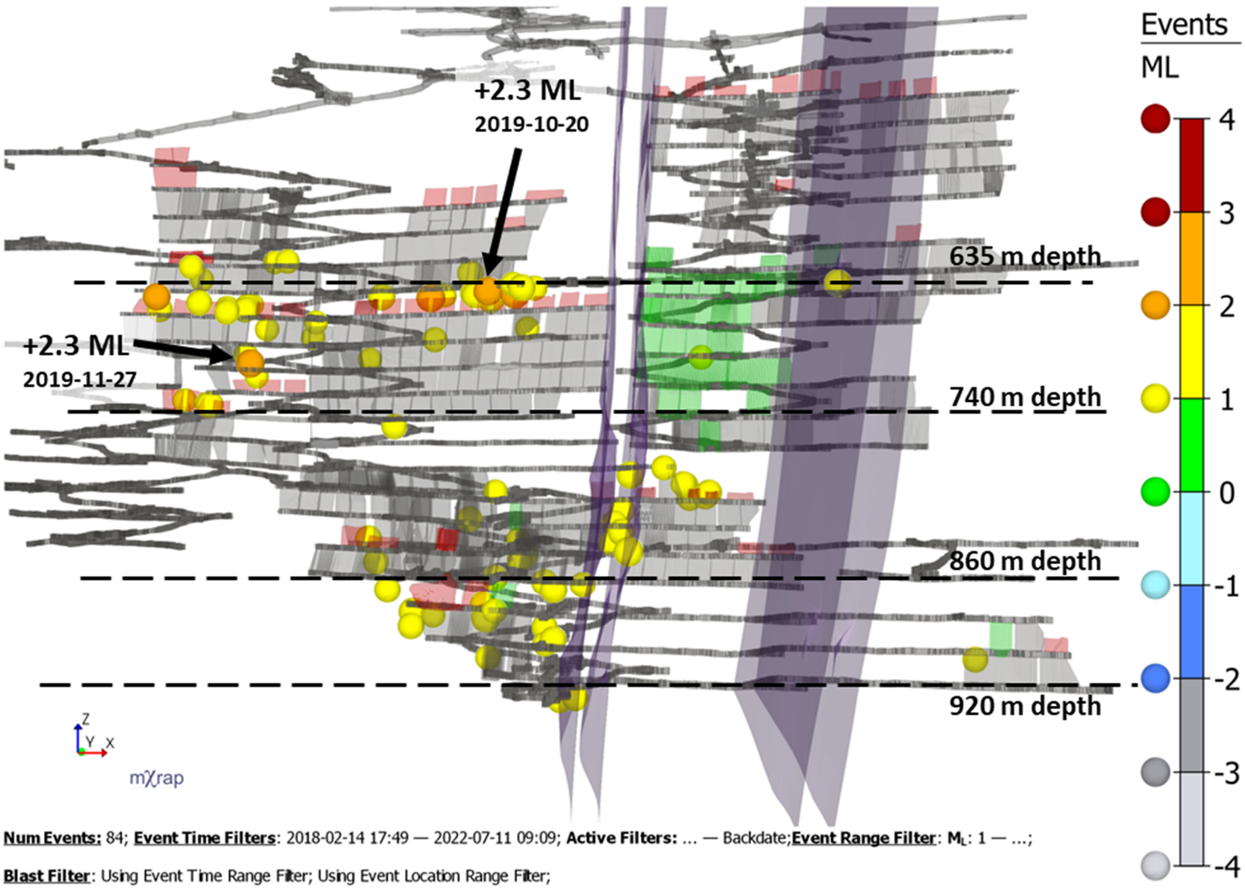


Figure 4 Overview of all large events with local magnitude >M_L1.0

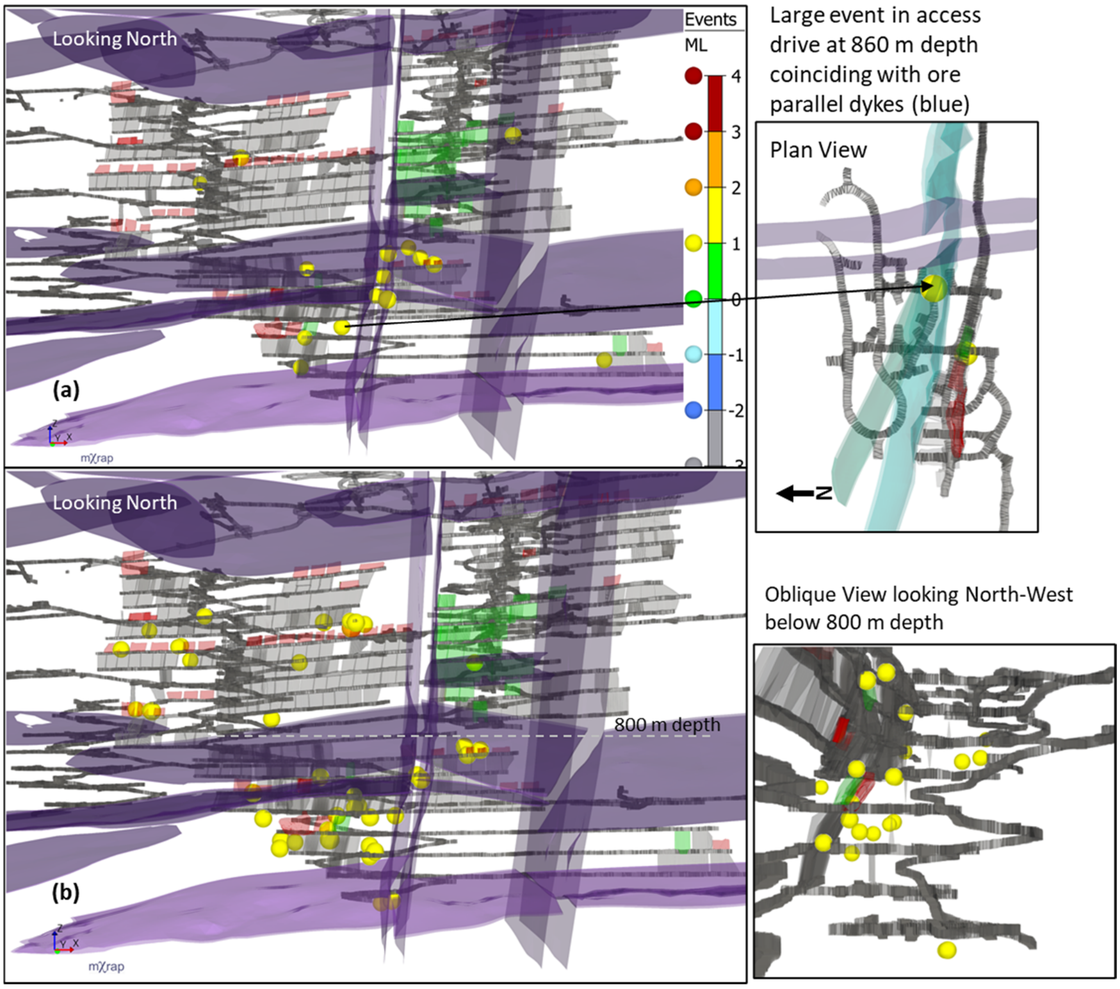


Figure 5 (a) Blast-induced large events (associated with mining activity within 24 hours of mine blast and within 50 m from blast location); (b) Triggered large events after 24 hours of any mine blast

A notable trend in the seismic response is the relatively large proportion of triggered (events with poor spatial or temporal correlation to a mine blast) seismicity compared to induced seismicity. While all the large events (>M_L1.0) could be spatially correlated to mining activities, many have poor temporal correlation with mining activity where dyke-associated large magnitude events have occurred days or weeks (or longer) after mining activities. This trend is particularly observed for events on the narrow dykes (sub-horizontal and ore-parallel). Examples of magnitude–time history charts are shown in Figure 6 for various spatial zones. The step-wise behaviour of the cumulative number of events is a typical indication of rock mass response to blasting, while a constant sloped cumulative number of events can indicate that seismicity is not triggered directly by mine blasting, which is commonly the case for structurally related seismicity. Multiple damaging incidents associated with the delayed events have also been reported and details are provided in Section 3.2. Large event mechanisms are not fully understood at this time since advance source mechanism analyses are not available, however, dyke-associated events with poor temporal correlation to mining blasts can be an indication of instability along geological features.

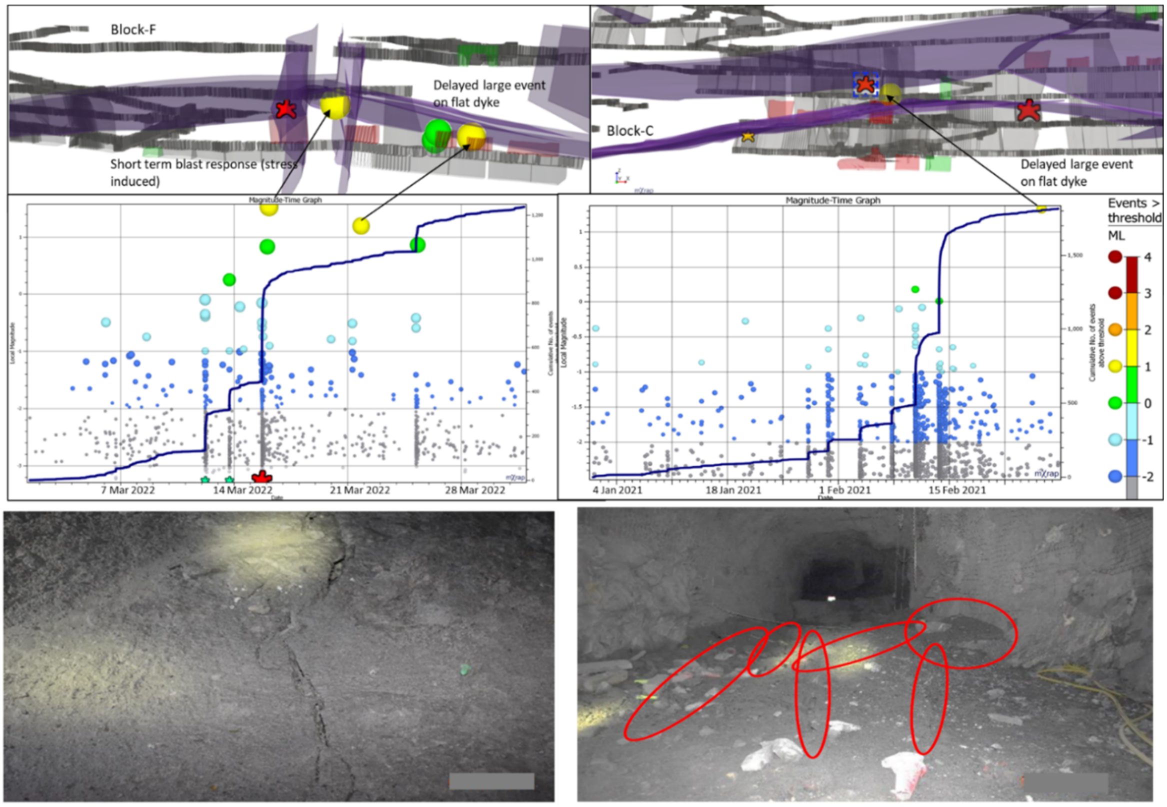


Figure 6 Illustration of example triggered large events (>M_L1.0) on dykes weeks after mine blasts and ground conditions showing damage propagation on the floor parallel to the exposed flat dykes

Detailed seismic analysis within mining blocks further demonstrated that the geological structure, blast size, and stoping front advance show a significant impact on seismic response. An example of comparative analysis of post-blast seismic response for five stope blasts on a single mining level at 820 m below surface is shown in Figure 7 with cumulative number of events in a 12-hour post-blast regression period plotted against distance from blast as the trigger source. The following observations are derived from the comparative analysis:

- Stope-A and Stope-B are blasted within the same time period (Q3-2020) and both occur at relatively low extraction near the abutment areas. However, the total number of post-blast seismic events for Stope-B is considerably higher as compared to the Stope-A. The influencing parameter between these two stopes is blast size (6,000 t versus 2000 t for Stope-B and Stope-A, respectively).
- Stope-A and Stope-C are both located between regional diabase dykes and have similar blast sizes. Seismic response for the Stope-C is greater as compared to the Stope-A. This difference is attributed to extraction ratio as well as the proximity of the Stope-C to the diabase dyke.
- Stope-C and Stope-D are located in either side of the diabase dyke where Stope-C is blasted first. The total number of events recorded after Stope-D is larger as compared to Stope-C, despite having a smaller blast size. It is also noted that the Stope-D blast-induced a M_L0.8 magnitude event located in diabase dyke. It is reasonable to conclude that the second stope blast adjacent to a dyke (i.e. transforming the dyke into a pillar) can generate large event seismic response.
- Stope-E is the final blast in the level. The total post-blast number of events is similar to Stope-D, however, it is noted that the seismic events for Stope-E blast have greater spatially dispersion (from the blast location), demonstrating an increasing area of influence for stress redistribution at higher extraction ratio within the diminishing pillar. Also, the Stope-E blast-induced multiple large magnitude events.

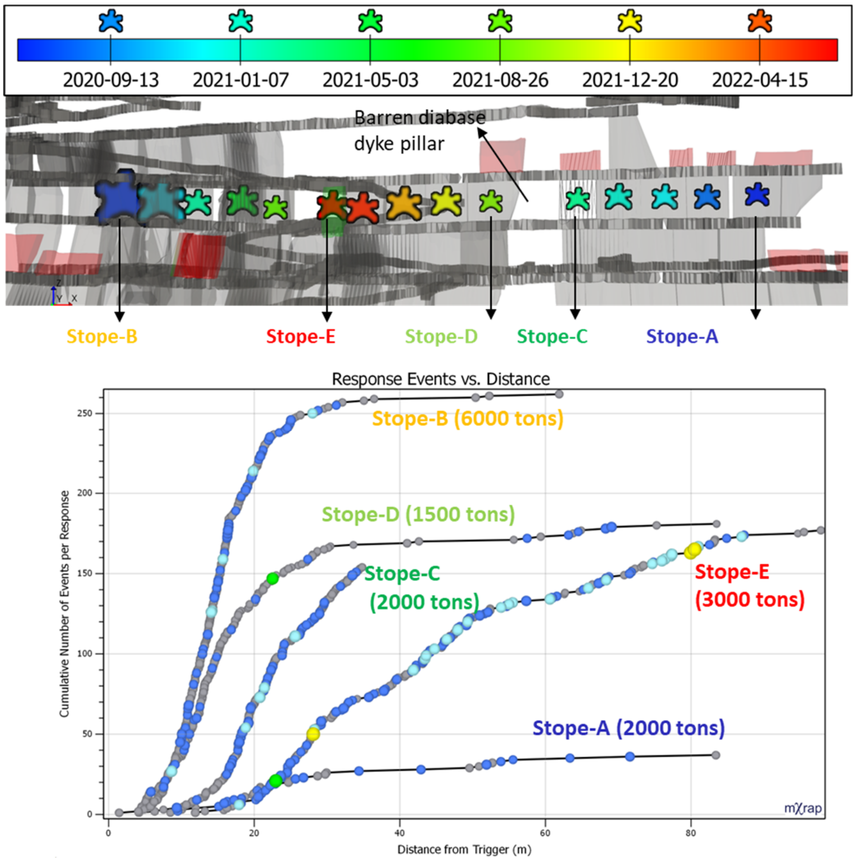


Figure 7 Post-blast seismic response (within a 12 hour time period) at 820 m depth. Relative blast tag size in top figure indicates relative tonnage which range from 2,000–7,000 t

3.2 Review of unusual occurrences

UO records offer site-specific information on realised rock mass behaviour that is to be considered for dynamic support design. The UO details have been reviewed with the objective of identifying causal factors contributing to each incident and interpreting the probable nature of the occurrence. Throughout the review, influencing parameters and the nature of rock mass response were correlated to identify factors deemed to have the greatest impact on dynamic stability.

Seventy-three UOs were reported between September 2017 and May 2022. Twenty-eight UOs occurred within/near development while all other UOs occurred within/near production stopes during remote mucking or before backfilling. UO incidents spatially coinciding with development have greater relevance to dynamic ground support design. Focusing on those incidents, 24 of 28 occurrences were reported to be below 785 m depth, preliminarily indicating a strong correlation between excavation instability and depth. Seventeen of the 24 UOs were damaging, where geomechanical characteristics are listed in Table 1.

The observed general trends in causal factors from the damaging events are summarised as follows:

- Stoping front at central diminishing pillars:
  - Significant ground movement and support system damage (including rockbolts and mesh screen) have been experienced within central diminishing pillars. Production blasts in central pillars have induced large seismic events with magnitude >M_L1.0.
- Structural geology (dykes):
  - Twelve of the 17 damaging UOs are observed to be associated with dykes (primarily the narrow flat-lying or ore-parallel dykes rather than the large regional diabase dykes). Large seismic

events located on (or near) dykes are often spatially and temporally correlated with the damaging UO incidents.

- Dyke-associated events may be attributed to structural slip mechanism. This conclusion is obtained based on the following observations (detailed back analyses, such as seismic moment tensor inversion [SMTI]) are not available):
  - Poor temporal correlation of several large events with mining activities.
  - Given that the flat and ore-parallel dykes are thin, a stress damage mechanism (as opposed to structural slip) may be questioned as there is likely insufficient dyke volume available for potential energy storage induced by mining stresses for some of the largest events (>>M_L1).
  - Poor rock mass quality observed at narrow dykes (as well as diabase dyke contact) from mapping campaigns. This observation supports a conceptual mechanistic interpretation of structural deformation rather than a brittle failure event (energy storage and release mechanism).
- Floor heave has been experienced in sills where flat dykes are below the floor. Examples of ground condition with crack propagation along the dyke alignments are shown in Figure 6.

- Sill pillars:
  - Seven of the damaging UOs occurred in the sill pillar at 800 and 880 m depth where uphole stopes are left open. All of these UOs include large magnitude seismic events; three of them are temporally correlated with mine blasts (occurring within a shift after nearby stoping) and are therefore likely induced by the stope blasting, and four of them are delayed events (not temporally correlated to mining activities) spatially associated with narrow dykes (these may be structural slipping triggered, but not induced, by stope blasts).
  - Timing of the large events in the area of the sill pillar at 880 m depth coincide with a relatively low extraction ratio below 880 m depth (i.e. area was not yet a diminished 'sill pillar'). Loading conditions on this level would likely have been influenced by stress redistribution incurred with excavation of the overlying mining horizon/block, with some impact from early mining advancement of the stopes below.
- Operational practices: blast size:
  - It is noted that there may be a correlation between seismic event rate and blast size, where larger blasts trigger more events. Large blasts, specifically >4,000 t located within the central pillars, are correlated with a substantial increase in seismic event rate.
  - Major ground deformations (including floor heave and buckling damages) are temporally and spatially correlated with large tonnage blasts in the central diminishing pillars. While a combination of influencing parameters likely contributed to these incidents (diminishing central pillar geometry and adverse dyke exposure likely to be the main controlling parameter), it is also reasonable to expect increased susceptibility to large deformations and increased seismic event rate following large blasts.

Table 1 Summary of unusual occurrences and influencing parameters interpreted based on seismic data review

Location	Damage nature	Large seismic events	Last mining activity	Near dyke	Diminishing central pillar	Sill pillar	High tonnage blast
Sill at 785 m depth	Floor heave	NO	1 shift	Flat dyke	YES	NO	YES
	Floor heave	NO	1 shift	Flat dyke	YES	NO	YES
Sill at 800 m depth	Ground support (GS) damage	YES	10 days	Flat dyke	NO	YES	NO
	GS damage	YES	1 shift	Diabase dyke	NO	YES	NO
	GS damage	YES	1 month	Flat dyke	NO	YES	NO
Sill at 860	Floor heave	YES	1 shift	Footwall open pit (OP) dyke	YES	NO	NO
Sill at 880 m depth	Noise	YES	1 shift	Adjacent to OP dyke	NO	YES	YES
	Missing rib pillar in CMS	YES	2 weeks	Adjacent to OP dyke	NO	YES	NO
	Spalling in back	YES	1 shift	OP dyke	YES	NO	NO
	Major bulking/ bagged screen/ broken bolt	NO	1 shift	NO	YES	NO	YES
	Noise	YES	10 days	OP dyke	NO	YES	NO
	Ejection	YES	8 days	OP dyke	YES	NO	NO
	Rockburst	YES	1 shift	Diabase dyke	YES	YES	YES
	FOG	NO	Virgin ground	NO	NO	NO	NO
Access 900	Not reported	YES	1 month	All (contacts)	NO	NO	NO
Ramp at 940 m depth	FOG	NO	Virgin ground	All (contacts)	NO	NO	NO
	Ejection	System down	Virgin ground	NO	NO	NO	NO
Decline at 945 m D	Rockburst	YES	Virgin ground	OP dyke	NO	NO	NO

4 Seismic domain delineation

The spatial delineation of the seismic domains relies on a general understanding of influencing parameters which have been identified by analyses of UOs and mine-wide seismic data, with refinement of spatial hazard at the local-scale according to proximity with conditions susceptible to the influencing parameters (sill pillars, diminishing pillars and dykes), as well as by temporary (ore sills) and permanent (all FW development) excavation classes for volumes not within the rock mass regions associated with influencing parameters. B-value analyses have been then completed for domained areas to define design events for dynamic ground support evaluations as listed in Table 2 (the application of these domained areas to dynamic ground support is described in Kalenchuk et al. 2023). An example analysis for dyke structures is shown in Figure 8 and a summary of the evaluations is provided below:

- Sill pillars: sill pillar volumes have been defined based on areas where horizontally extensive pillars of two level heights or less have been created over the monitoring period. This two-level dimension has been defined based on observations of the spatial extent of seismic reaction after mine blasts in the sill pillar, as well as to account for the inherent uncertainty in seismic source location error.
- Dykes: dyke-associated seismicity for this domain analysis has been defined by events located within 20 m of the large regional dykes and within 25 m of the narrow (flat and ore-parallel) dykes (Figure 8). These boundaries have been selected based on evaluations of high apparent stress (HAS) events proximal to the dykes.
  - Cumulative frequency distributions of apparent stress for different mining zones are shown in Figure 9a which varies from roughly 1 kPa to 1 MPa. Hudyma & Brown (2020) use the 75th percentile as the HAS threshold to characterise stress changes over mining period. Considering a mid-range envelope of all the mining zones, this analysis reveals a 75th percentile of 60 kPa as HAS threshold.
  - Figure 9b shows the blast induces events (24 hours following blasts) exceeding HAS. Blasts located greater than 20 m distance from diabase dykes do not trigger seismicity in the dyke.
  - Seismic response to significant events (24 hours following a seismic event magnitude >M_L0.5) with apparent stress exceeding the 60 kPa threshold is shown in Figure 9c. The data relative to flat dykes are distributed within a 20 m distance range.
- Diminishing central pillars: diminishing central access pillars in this study are considered to be within four stopes on either side of the ore sill access.
- Lower extraction abutment zones: seismicity in the plane of the ore (proximal to temporary development) that falls outside of the sill pillar and central diminishing access pillar domains spatially coincides with the mining zones abutments. This spatial domain includes all data in the plane of the ore outside of all volumes associated with influencing parameters (sill pillars, diminishing central access pillars and proximal to dykes), and is divided into two sub-domains, above and below 860 level.
- FW development (access and ramp): B-values analysis for seismicity in the FW (i.e. relevant to permanent development) which is not influenced by dykes (or pillars) is differentiated in sub-domains as above and below 860 m mining depth.
- Barren stope pillars: barren pillars can also act as local stress concentrators and show dynamic response.

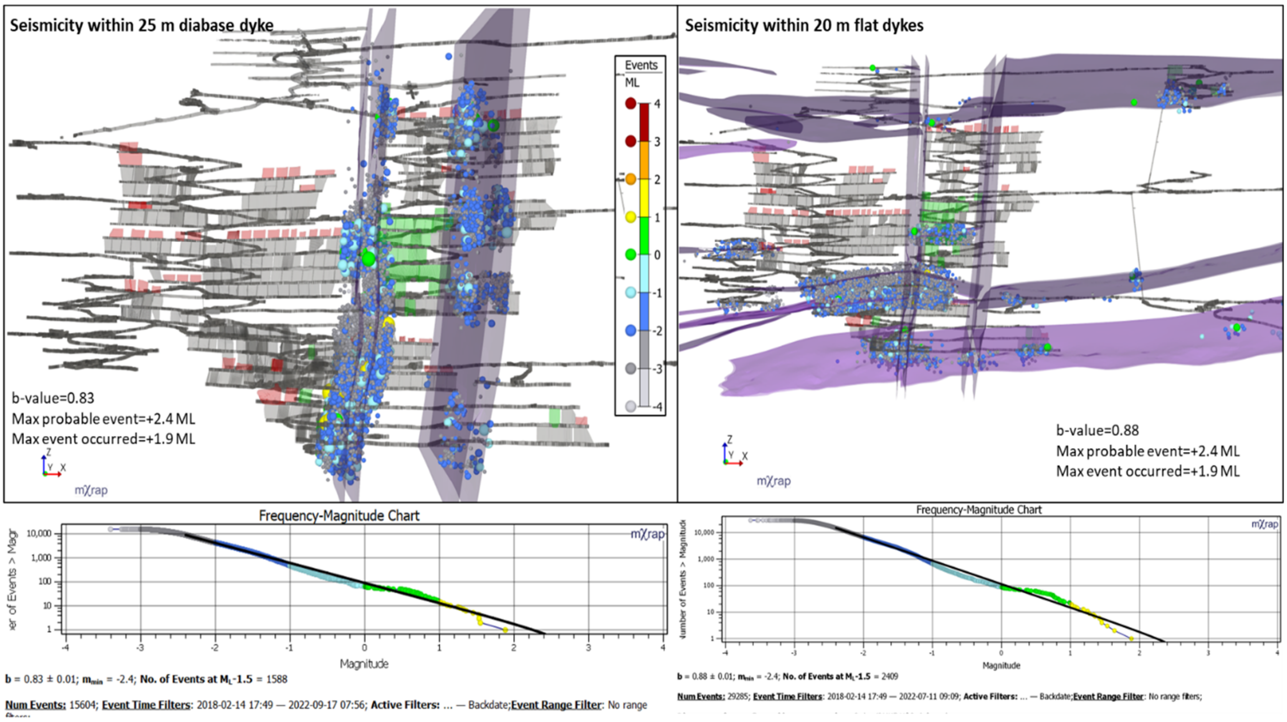


Figure 8 Seismicity in dyke influence zones and frequency–magnitude chart with B-value analysis

Table 2 Estimation of maximum probable event in seismic domains from frequency–magnitude analysis, and maximum observed event (in brackets). The event magnitudes that are considered for classifying seismic hazard are shown in bold

Seismic domain		Maximum seismic magnitude (M_L)		B-value
		All data	Excluding other causal factors	
Sill pillars		**+2.6** (+2.3)	–	0.77
Diabase dyke		**+2.4** (+1.9)	–	0.83
Flat dyke		**+2.4** (+1.9)	+1.4 (+1.6)	0.88 (1.14)
Ore-parallel dyke		+2.0 (**+2.3**)	+1.5 (+1.9)	1.12 (1.19)
Barren stope pillars with low width/height		**+1.5** (+1.2)	–	1.14
Diminishing central access pillars (high extraction within four stopes of the access)		+1.5 (+2.3)	+1.2 (**+1.3**)	1.16 (1.23)
Abutment mining	Above 860 m depth	+2.0 (+2.3)	+1.5 (**+1.0**)	1.04 (1.15)
	Below 860 m depth	+1.5 (+1.9)	+1.0 (**+1.3**)	1.06 (1.14)
Footwall development (ramp/access)	Above 860 m depth	+1.0 (+0.9)	+0.8 (**+0.9**)	1.21 (1.35)
	Below 860 m depth	+1.8 (+1.6)	**+1.5** (+1.4)	1.02 (0.83)

Note: There is inherent overlap of data between spatial domains, so data filtering/exclusion is conducted where applicable to avoid overconservative estimate of the design event.

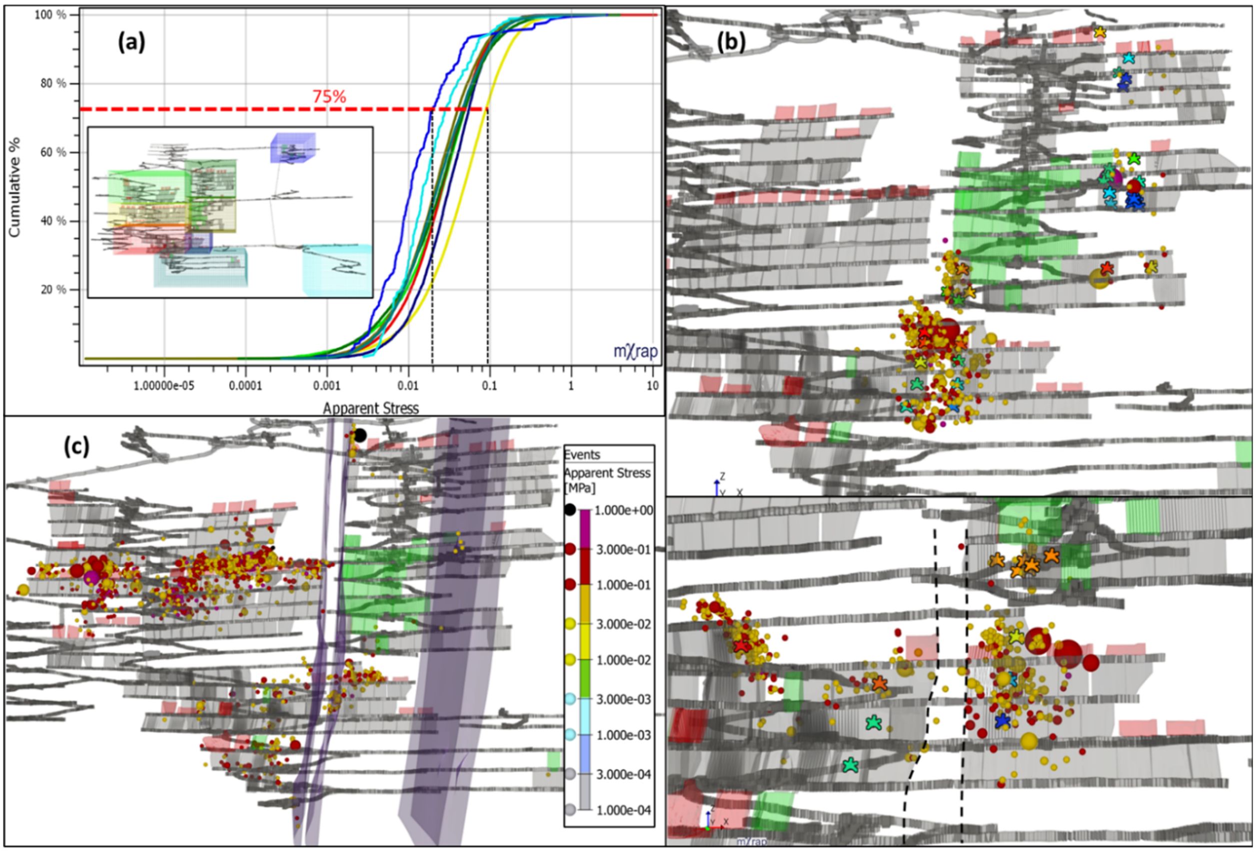


Figure 9 (a) Cumulative frequency distribution of apparent stress for different mining blocks; (b) Mine blasts within 20 m (top) and 40 m (bottom) of diabase dykes and blast-induced HAS events; (c) HAS seismic response following significant triggered/delayed events (magnitude >M_L0.5)

From the maximum probable events and maximum observed events listed in Table 2, three seismic hazard domains based only on event magnitude ranges are defined as listed in Table 3. Additional analyses (such as back-analysis of large event source mechanisms) are required to improve hazard domains with consideration for mechanism. The design events for dynamic support analysis applications have utilised the maximum (experienced or probable) for grouped domains.

Table 3 Seismic hazard domains and associated design events

Seismic hazard category	Seismic hazard domains	Design event (M_L)
Static	Development above 635 m depth	NA
LOW	FW development above 860 m depth Abutment mining above 860 m depth	+1.0
MODERATE	FW development below 860 m depth Abutment mining below 860 m depth Diminishing central pillars Barren stope pillars	+1.5
HIGH	Sill pillars (top two levels) Exposure to dykes (flat/ore parallel/north–south diabase)	+2.6

5 Discussion and conclusions

In this paper, seismic data analyses are presented for a deep Canadian mine to identify influencing seismic response parameters, which are then applied to mine-wide seismic domain delineation and determination of maximum probable design event in each domain for strategic dynamic support design applications. The key influencing parameters on seismic response were solely characterised based on spatial and temporal analyses of the seismic data. The following considerations are noted:

- A notable trend in the seismic response was the relatively large proportion of triggered seismicity (with poor spatial or temporal correlation to a mine blast) compared to induced seismicity. Triggered seismicity was characterised as a seismic response with poor temporal correlation to mining activities. It was apparent that many of the largest triggered events may be structural slip mechanisms associated with narrow dykes or dyke contacts. However, mechanism back analyses like SMTI analysis were not available at the time of this study. Such back-analysis would be critical as improved understanding of mechanism enables strategic design considerations, focused on mitigating the associated hazards through sequence and exposure control in addition to dynamic support as the last hazard management component.
- Seismic data analysis clearly show that some large magnitude seismic events could be associated with time-dependency deterioration of remnant rock mass volumes in sill pillars (for example skin and rib pillars). This observation demonstrated that seismic hazard would not fully dissipate when mining was complete, and mine workings in proximity to depleted sills and remnant pillars should be maintained with effective support systems and/or establish permanent barricades to restrict access.
- Mining geometry and geological structures have been identified as having the greatest influence on seismogenic ground response. There was a good spatial correlation between large seismic events and excavation damaging incidents with the dykes (diabase dykes, sub-horizontal dykes, and ore-parallel sub-vertical dykes) and pillars (sill pillars and diminishing central access pillars). In some cases, the occurrence of dykes and pillars are spatially coincident, rendering the relative significance of each individual influencing parameter or their combined effects unresolved (given the absence of detailed back analyses).
- Depth was identified as a significant factor on seismogenic ground response. Based on relatively high seismic response to early-stage mining and advancing development, mining depth was considered a contributing factor for ground behaviour transition to dynamic loading. Further to analyses of seismic history, the current study can be improved by relying on numerical stress models for seismic hazard domaining and to predict the evolution of seismicity over mining periods of interest. The stress induced on an excavation, or imposed on a pillar or structure proximal to an excavation, over the service life of that excavation, is a key input to seismic hazard. The evaluation of stress conditions prior to excavation construction, and the evolution of stress conditions over an excavation's service life requires three-dimensional stress simulations.
- Operational practices were correlated to the intensity of blast-induced seismic response based on temporal seismic analyses. Large blasts, specifically >4,000 t production and located within the central pillars, have triggered substantial increases in seismic event rates. This observation was particularly important for high hazard seismogenic zones. Seismic analysis allowed for providing tactical recommendations, such as limiting blast size in high extraction ratio areas or proximal to dykes, to mitigate the potential for elevated seismic response in high hazard areas.

The seismic domaining approach applied in this paper provides general guidance for conceptual spatial understanding of seismic hazard and probable design event for utilisation in dynamic support design. Next steps for seismic hazard management and support utilisation are the development of seismic hazard (or rockburst hazard) maps, requiring spatial evaluation of seismic potential and excavation vulnerability. Seismic potential requires characterisation of rock mass and structural seismic response to mining (as addressed in this paper) related to geology (lithology and distance to structure), stress (in situ and mining-induced from numerical stress modelling) and mine geometry. Excavation vulnerability is influenced by void geometry, support system capacity and support system condition. Enveloping seismic domaining with hazard mapping will deliver targeted dynamic support system designs, effectively managing seismic hazard in a safe and economical manner.

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