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A case history of a major fault slip rockburst

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Abstract

On 15 March 2022, a Nuttli magnitude (MN) 3.5 fault slip seismic event occurred in a sill pillar at Coleman Mine. The mine was in the process of extracting a sill pillar by removing a slot from the core of the pillar, with the goal to de-stress it. While mining the second de-stress panel, a MN3.5 fault slip seismic event occurred along a previously unknown geological structure. The seismic event caused significant shakedown damage to nearby excavations.

The objective of this paper is to summarise the initial sill pillar extraction design, the rockburst event, and the results of the investigation to understand the incident. Finally, the implementation of key lessons learned and the path forward for the sill pillar are shared in the hope that geotechnical practitioners across the industry can benefit when faced with similar conditions at their operation.

Keywords: *seismicity, rockburst, fault slip, sill pillar, deep mining*

1 Introduction

In deep mines, seismicity and rockbursting can present a significant risk to people and the business. When rockburst incidences occur, it is important to stop, investigate, and understand the root cause. Lessons learned are a key aspect of rockburst investigations and applying them are critical to ensuring the likelihood of similar incidences are reduced or eliminated.

This paper presents a major rockburst at a deep mine in the Sudbury Basin. The purpose is to share the sill pillar extraction strategies, rockburst incident and lessons learned and how they have been applied to improve designs and process. It is the hope of the authors that other geotechnical practitioners can apply the presented learnings in their operations or project.

2 Coleman Mine

The Vale Base Metals Coleman Mine is a moderately deep base metals mine operating in Sudbury, Ontario, Canada. Nickel-copper-precious ore is extracted at a rate of roughly 3,600 t per day at depths between 1,000 and 1,800 m below surface. Previous publications by Landry & Reimer (2019) and Townend & Sampson-Forsythe (2014) have described the mine and its seismic risk management practices. Coleman has been in operation since 1970. The active orebodies have been in production since early 1990 and several of them are at a late stage of extraction resulting in mining of highly stressed sill pillars. Currently, the primary mining methods include open stoping and mechanised cut-and-fill with cemented hydraulic backfill. The primary ground control challenges are those associated with high stress conditions with the resulting hazard being rockbursting.

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2.1 Mine seismicity

Seismicity causing rockbursting which results in injury to personnel, damage to equipment and/or infrastructure, and/or business interruption is one of the critical risks at Coleman Mine. Seismicity is prevalent due to the mining depth, high horizontal stress regime, high extraction ratio, and high rock strength.

A critical component of the mine's seismic risk management plan is the seismic monitoring system. Coleman operates an ESG Solutions mine-wide seismic system consisting of three individual sensor arrays (one per main mining zone) of uniaxial and triaxial accelerometers and geophones. Seismicity generally only occurs in the vicinity where mining is occurring. The 153 and main orebodies have higher extraction ratios compared to the 170 orebody, and it can be observed that the large seismic events are typically located in major pillars and along abutments or faults. Figure 1 shows a long section of Coleman Mine with seismic events (MN > 0) for a three-year period (2020–2023) and important faults superimposed. Note, the faults in Figure 1 are sketches only.

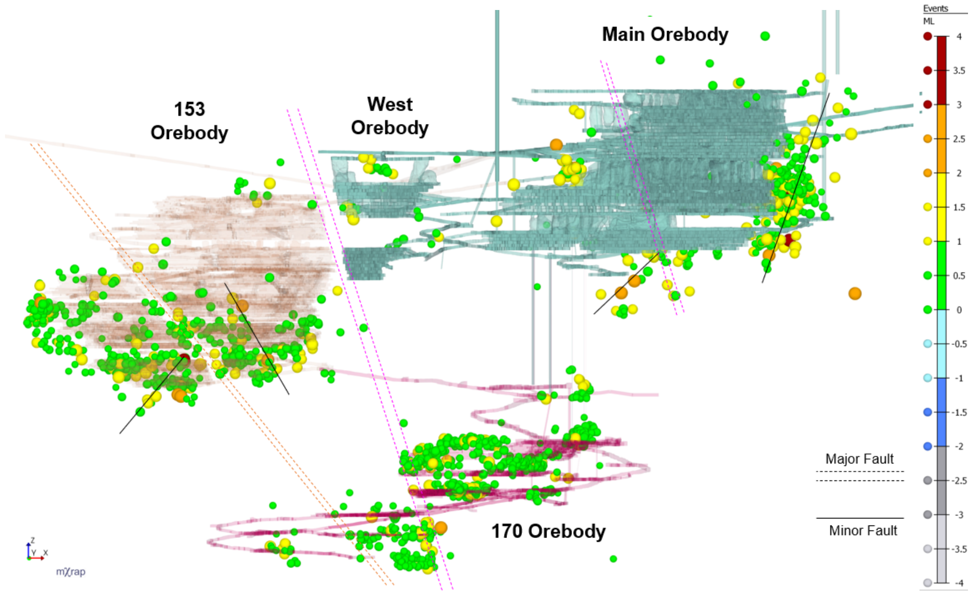


Figure 1 Long section of Coleman Mine showing active orebodies and seismic events with magnitude greater than 0MN. Major and minor faults sketched

Moderate magnitude seismic events (MN < 1.5) generally manifest themselves by rock fracturing in the form of slabbing ('onion skinning' or 'spalling') in drift development or local pillars (Masethe et al. 2024). Most large events (MN > 2.0) are typically observed or classified as slip events on pre-existing faults (Yao et al. 2014).

To help describe the primary rock mass failure mechanisms that occur at Coleman Mine, Figure 2 shows a plan view of a narrow vein cut-and-fill mining level with the development headings following the ore vein. The rock mass response is displayed by clustering of seismic events around openings which occur as fracturing where development mining is taking place. Reaction to the major fault on the left of the plan is observed as more sporadic in location along the fault contact.

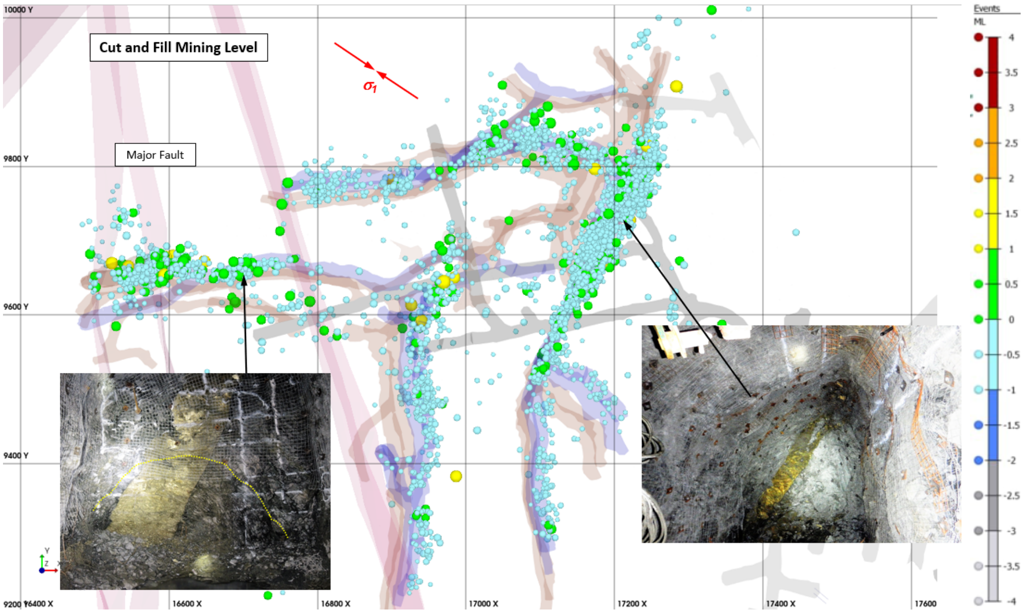


Figure 2 Plan view of a narrow vein cut-and-fill mining level at Coleman Mine (1,700 m depth). Seismic events for the life of the cut are coloured by magnitude (MN > −1). Typical field observations shown in the photo as high stress spalling conditions

A more complicated mining geometry is shown in Figure 3, a highly stressed sill pillar on the left and a fault system, abutment, and moderately stressed sill pillar on the right of the level. Notably, the major dyke cutting through the core of the orebody has not generated seismicity in its core.

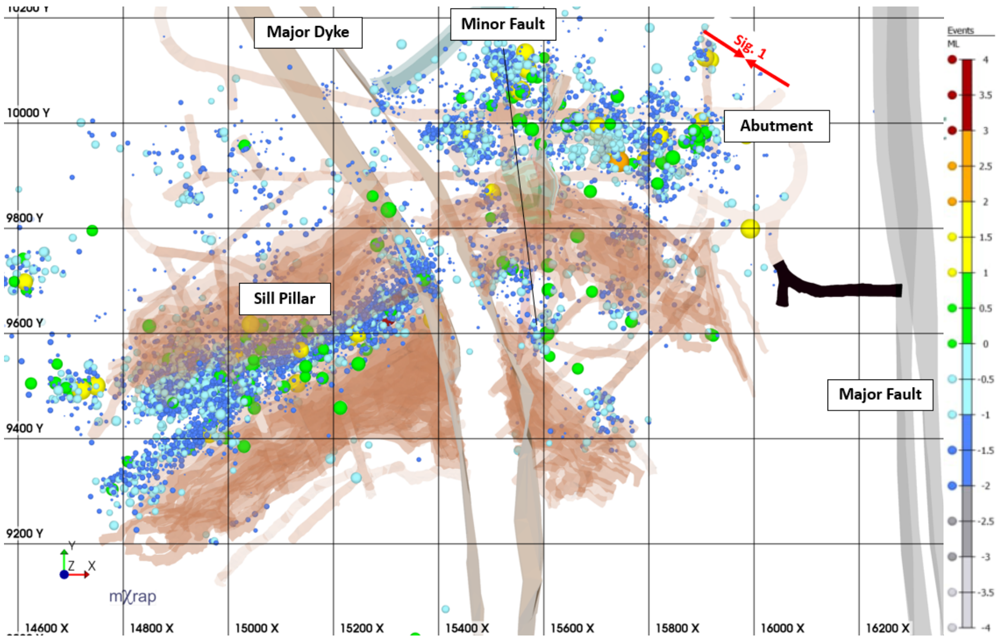


Figure 3 Plan view of a heavily mined sill pillar level at Coleman Mine (1,600 m depth). Seismic events for a two-year period shown and are coloured by magnitude (MN > −3)

2.2 153 orebody

This paper focuses on the 4945 Block 2 Sill Pillar in the 153 orebody and highlights the challenges of mining in a sill pillar environment. The 153 orebody is narrow vein nickel-copper-precious metals deposit and is bounded on the east by a major fault (Bob’s Lake Fault) and is bisected by a major dyke (olivine diabase dyke). The orebody is an assemblage of relatively flat dipping and irregular massive sulphide veins hosted in Sudbury breccia, granite gneiss, and some diabase. Mechanically, the host rock properties are strong and competent (~220 MPa). In the ore zone, rock mass strength decreases with increasing vein size. Trunk vein areas (~120 MPa) produce more prominent stress fracturing around excavations and stockwork areas more like the host rock. Mining is currently taking place on five levels at depths between 1,200 and 1,600 m below surface. Overhand cut-and-fill, underhand cut-and-fill, and open stoping are the three mining methods utilised. Figure 4 shows a long section of the 153 orebody and the generalised seismic hazard levels (based onsite experience and analyses) in the various mining blocks along with important geological structures.

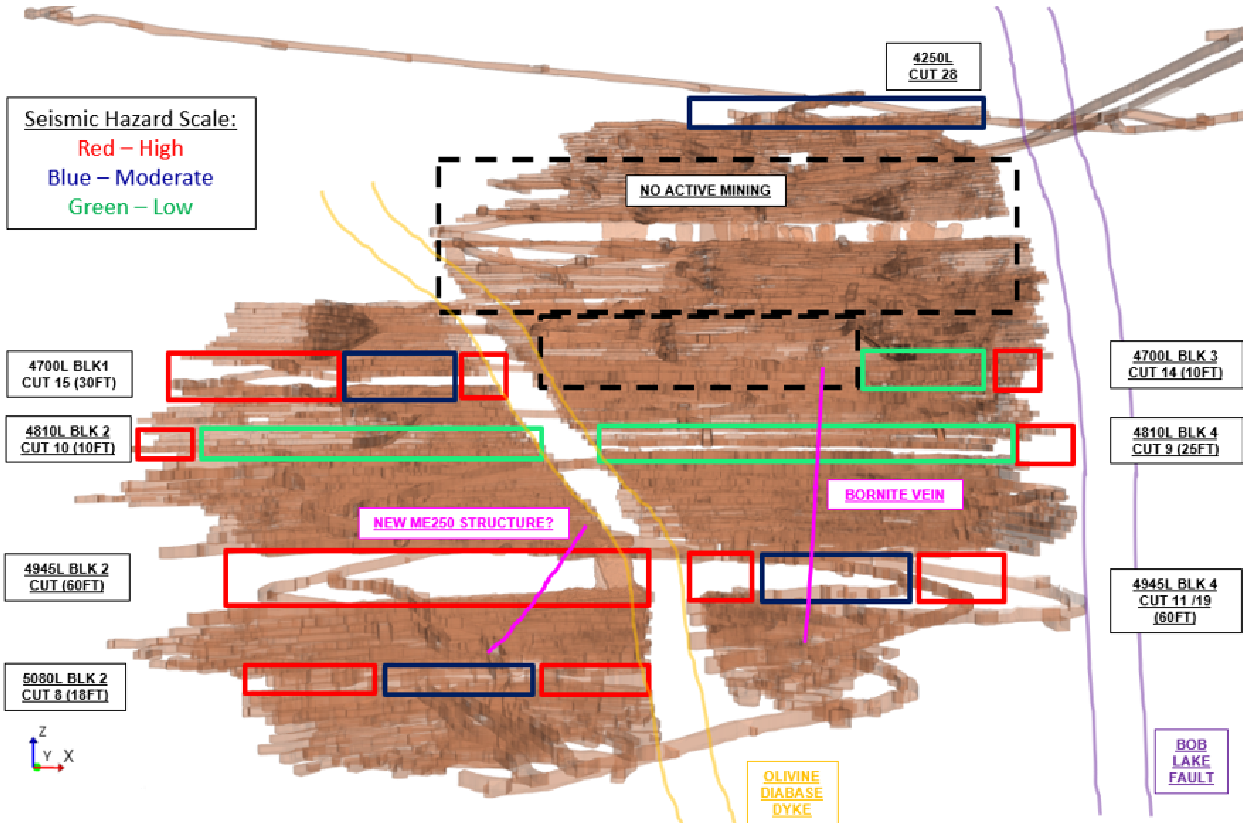


Figure 4 153 orebody looking north. Generalised seismic hazard levels in the various remaining ore blocks along with important geological structures

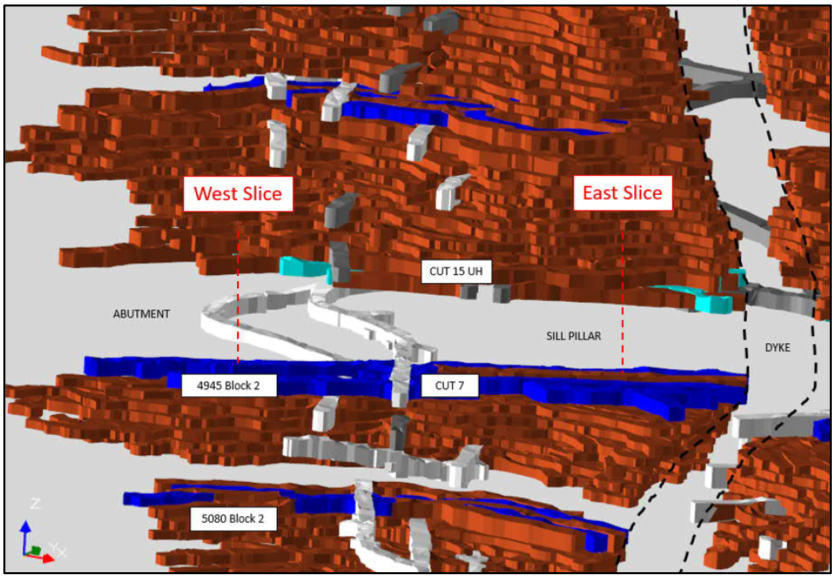
Mining has been taking place in the 153 orebody since the early 1990s. Orebody infrastructure was driven in the footwall, which includes a haulage ramp, six main extraction levels that are vertically spaced roughly 36 m apart, ladderways, ventilation raises, and sublevel access ramps. Each level was divided into two to four mining blocks for productivity reasons and mining initially took place using narrow-vein overhand cut-and-fill utilising one-boom jumbos for development drilling and handheld equipment (jackleg/stoper) for ground support installation. As mining progressed, sill pillars were established between the mining levels, and as the pillar geometries diminish, the mining plans have evolved to manage the changing ground conditions. Seismicity management practices in the 153 orebody has been previously documented by Townend & Sampson-Forsythe (2014). In the last 15 years, several strategic design strategies have been employed to mitigate seismicity in the sill pillars, which include:

1. conversion to open stoping
2. conversion from overhand cut-and-fill to underhand cut-and-fill
3. regional de-stress curtains (drilled and/or blasted).

Additionally, a transition has been made from handheld ground support installation to mechanised installation (deck/boom bolters) to improve safety. To date, one sill pillar has been extracted with open stoping and four with regional de-stressing (three drilled curtain and one large-scale choke blast) which allowed cut-and-fill to continue. There are currently three major sill pillars remaining in the 153, the following section highlights the 4945 Block 2 Sill Pillar.

2.3 4945 Block 2 Sill Pillar

The 4945 Block 2 Sill Pillar is located in the lower half of the 153. The ore zone has an average thickness of 26 m and dip of 30°. Towards the abutments, the ore thins down and flattens (roughly 18°). An olivine diabase dyke bisects the orebody, and the Bob's Lake Fault bounds the ore on the east. Figure 5a shows a general long section of the sill pillar from the hanging wall side and Figure 5b an isometric view looking diagonally from the hanging wall, highlighting pillar loading between mining horizons (FLAC3D numerical model output).



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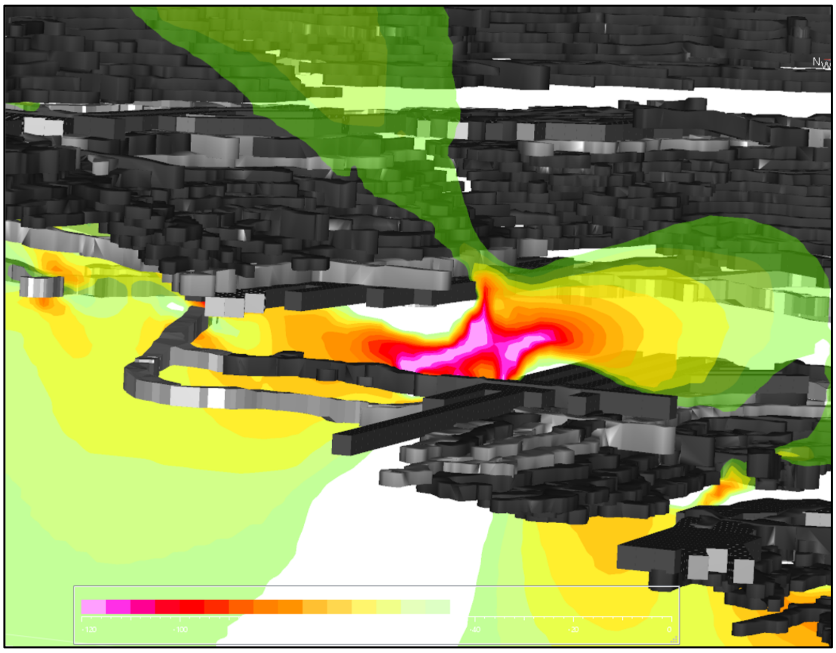


(b)

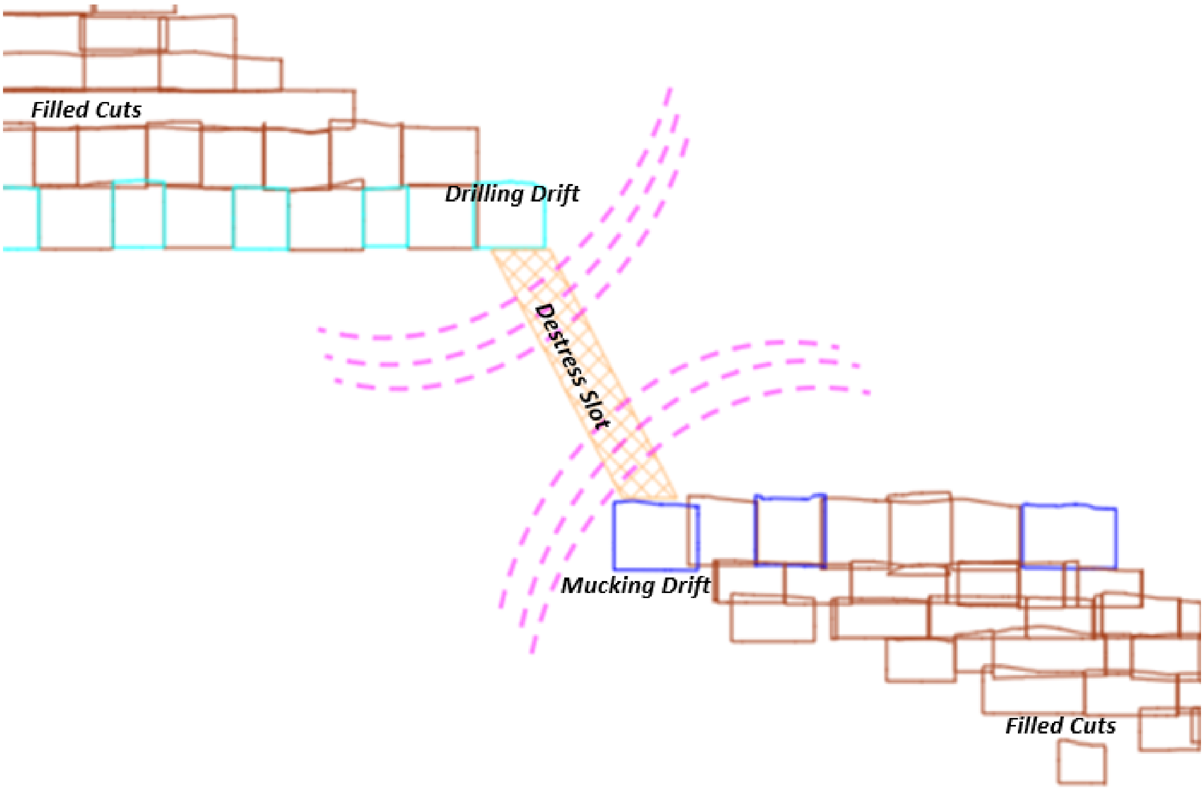
Figure 5 (a) Isometric (long) view looking North showing configuration of the 4945 Block 2 Sill Pillar. The sill height is 18 m, strike length is 120 m (2020); (b) FLAC3D numerical model output showing existing excavations (2020) with a vertical slice through the pillar core. Deviatoric stress – pink being roughly 100 MPa deviatoric stress

Prior to sill pillar mining, the block had been mined using overhand and underhand cut-and-fill (drift-and-fill) creating a vertical diminishing pillar. When the pillar was at a vertical height of 27 m a decision was made to complete two more cuts from each mining front. To help manage high stress ground conditions, the cut height was changed to 4.5 m in both cuts to allow for mechanised equipment. Local experience obtained from mining several other sill pillars previously indicated that at a vertical pillar height greater than 18 m (at similar orebody widths) extraction would be manageable. At a height less than 18 m vertical (or width:height < 1.5) the sill pillar would begin to yield. Several extraction options were considered for sill pillar recovery. The method description and ground control positives and negatives are listed in Table 1.

Table 1 Initial sill pillar extraction options considered

Method	Description	Positive	Negatives
Drillhole 'curtain'	A series of holes drilled through the pillar core or footwall (typical design was a 150 mm diameter drilled on 610 mm spacing)	Method had been used previously and shown to reduce stress levels	Does not completely remove the driving stress. Challenge to keep holes aligned
Transverse or longitudinal open stoping	Establish sills on the top and bottom horizon and mine bulk stopes	Lower exposure than cut-and-fill. Can cut-off the driving stress to mine in either side in a stress shadow	Complex geometry
In-ore slot	Establish longitudinal sills on the top and bottom horizon and mine a slot through the pillar core	Lower exposure than cut-and-fill. Cuts off the driving stress	Complex geometry
Hanging wall slot	Establish hanging wall access, drill and blast a vertical slot to shadow the sill pillar	Lower exposure than cut-and-fill. Method had been used previously	Does not completely shadow or cut-off the stress

The in-ore slot was the selected option for the 4945 Block 2 sill recovery given the geotechnical and operational inputs. The design was to longhole a thin ore slot in a series of stopes through the entire sill pillar sequenced from the dyke to the abutment. Once the slot was complete for the entire sill pillar, the remaining ore would be mined in a stress shadowed state (planned to be cut-and-fill post in-ore slot). See Figure 6a showing conceptual design of the in-ore slot, and Figure 6b an isometric view of the final design.



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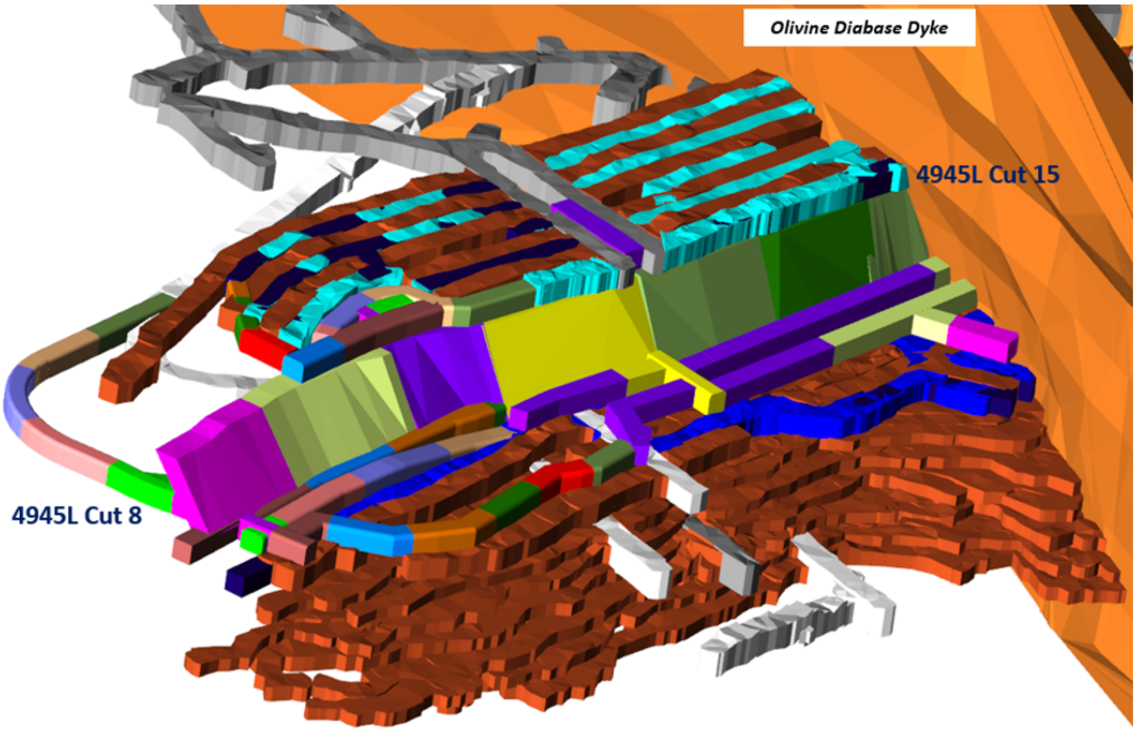


(b)

Figure 6 Initial sill pillar design. (a) Section view showing conceptual design of the sill pillar in-ore slot. Dotted pink lines highlight stress flow direction prior to mining out the slot; (b) Isometric view of the 4945 Block 2 Sill Pillar. Showing existing cuts in brown, and the de-stress slot (coloured)

From a ground control standpoint, the design considered several main elements, general layout and placement of drill and mucking drives, ground support, stope design, and ground monitoring.

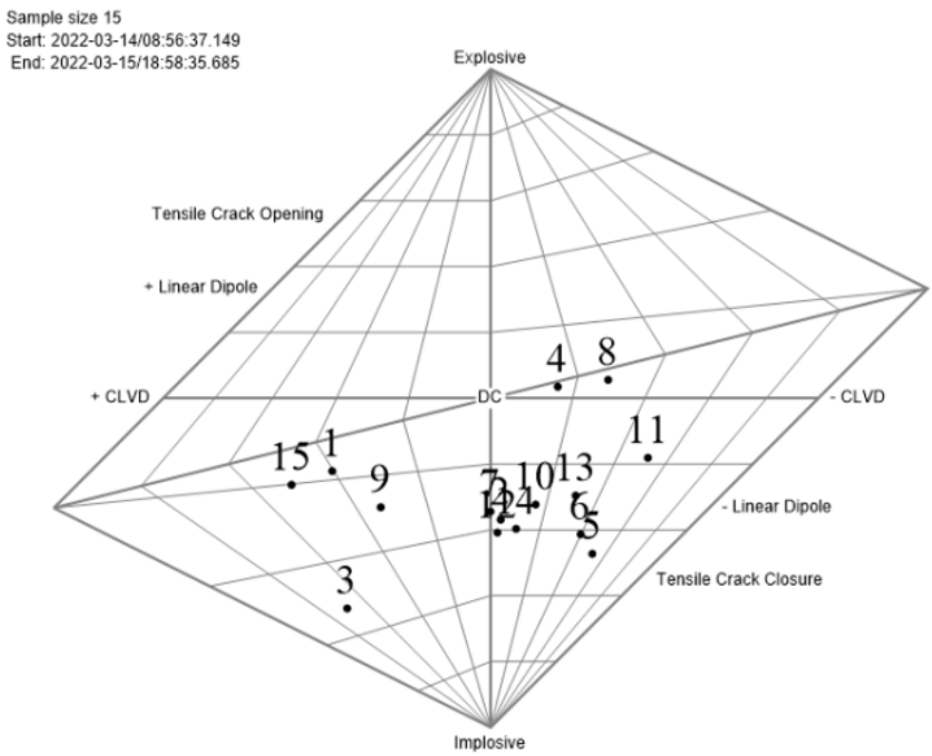
- The topsill development for downhole drilling utilised the final cut-and-fill pass on the hanging wall side of the orebody. The bottom sill development for stope mucking utilised the final cut-and-fill pass on the footwall side on the last overhand cut. Development following tight to the fill, not creating internal pillars which would cause further stress driven geometrical issues.
- A stope width of 4.3 m was selected for the slot to ensure control measures could be put in place for future cut-and-fill mining against the filled stope. The pillar was broken into several stope cycles with each being backfilled.
- Stope blasting was slot-slash to ensure vertical pillars were not created inside the sill pillar.
- As part of the design the structural geology was reviewed. At the time of the review there were no known major faults in this sill pillar. Jointing was also deemed minimal in the host rock (RQD > 80), and a major dyke was known present on the edge of the sill.
- Major ground support upgrades were completed prior to the commencement of sill pillar mining. Upgrades were completed to key areas within the sill pillar including the drill/mucking drives. The ground support design consisted of dynamic bolts (yielding inflatable or paddle bolts), 6-gauge screen and 0-gauge strapping.
- Ground monitoring instrumentation, seismic monitoring was employed, and serval large-scale system upgrades were completed to ensure a high sensitivity and accuracy was achieved in this sill. A stress cell array was also installed in the pillar core to monitor the stress redistribution in the sill pillar with live monitoring wired to a surface station.

3 ME-250 rockburst

While executing the in-ore slot, a 3.5 Nuttli magnitude seismic event occurred in 4945 Block 2 and resulted in a major rockburst which was investigated under the name ME-250. Prior to the ME-250 event, the first de-stress stope had been successfully mined and backfilled and the second stope had been drilled-off. A worker was measuring holes when the MN3.5 event occurred. Due to the high potential of this rockburst incident, a formal independent investigation team was formed to investigate the incident (Vale Base Metals 2022). This section summarises the conclusions from the investigation.

3.1 Interpretation of seismic sources

Prior to the ME-250 event, the seismic data suggested a failure mechanism primarily driven by rock fracturing or sill pillar loading (strain events in the sill pillar). However, the MN3.5 event resulted in a series of seismic events along a distinct observable plane (now named the ME-250 fault) in the footwall of the orebody which was not previously observed. This indicated that the failure mechanism may have been a fault slip event. A seismic moment tensor inversion solution was not possible for the large event due to the complexities in the waveform, however 15 mechanism solutions for associated foreshocks and aftershocks were determined. Prior to the MN3.5 event, the ME-250 fault had not been apparent during routine seismic analysis or geologic reviews of drillcore carried out by engineering staff or during routine mapping of underground development drives. Figure 7 shows the Hudson plot produced for larger seismic event precursors and aftershocks, as well as a frequency–magnitude relation for the 4945 Block 2 Sill Pillar for two years prior to the ME-250 event.



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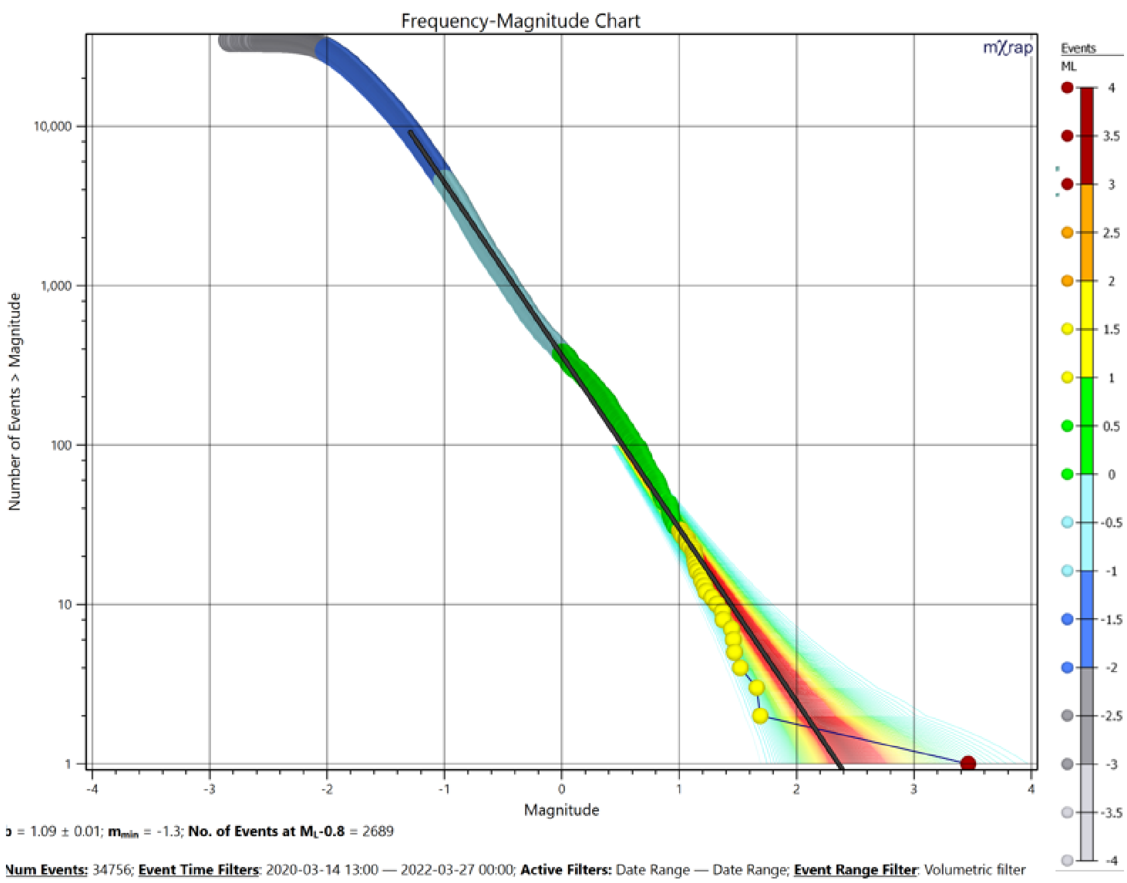
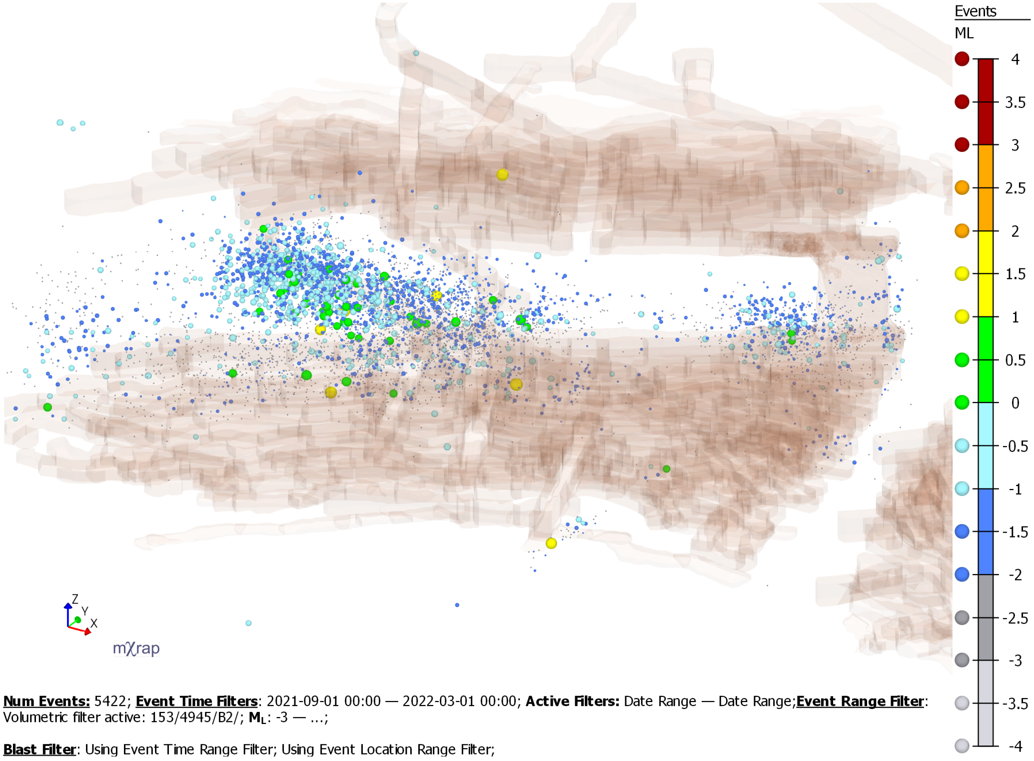


(b)

Figure 7 (a) Hudson plot for the ME-250 seismic event precursors and aftershocks. Most events are shear slip with closure and two are pure shear failure; (b) Frequency–magnitude relation for the 4945 Block 2 Sill Pillar for two years prior and two weeks following the ME-250 incident

Figure 8 shows the seismic data before and after the ME-250 event.



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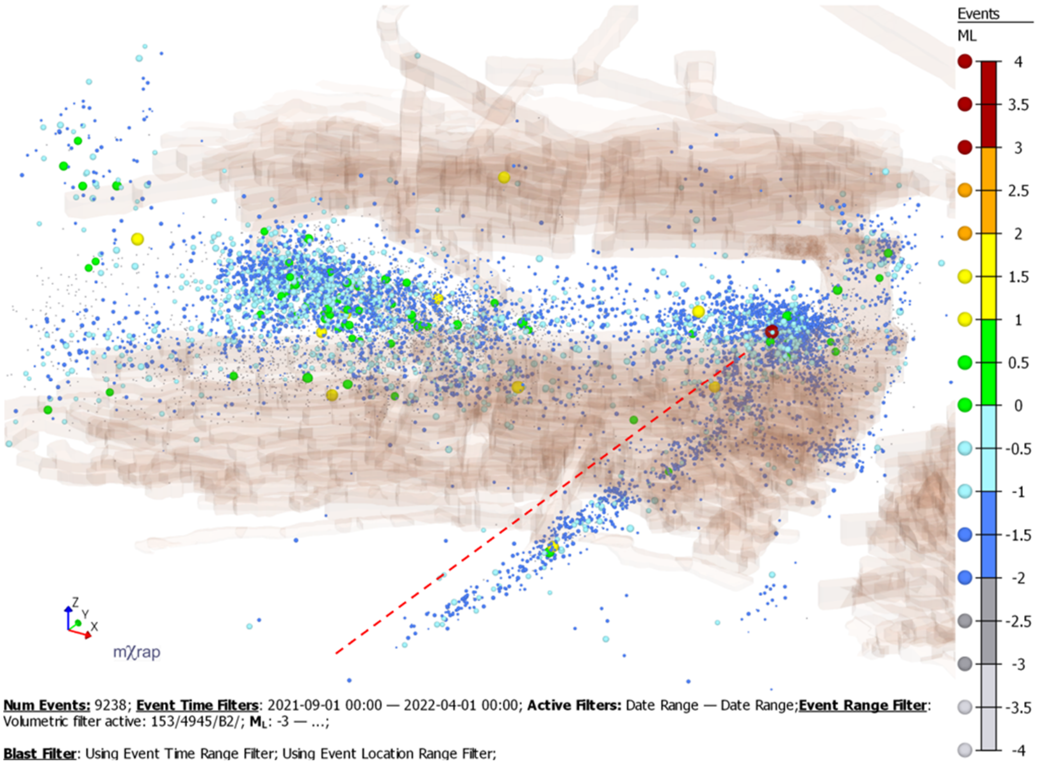


(b)

Figure 8 Isometric views looking north from the hanging wall of the orebody. (a) Seismic events coloured by magnitude (six months prior to ME-250); (b) Seismic events coloured by magnitude (six months prior to ME-250 and one month after) where the observable seismic trend (ME-250 fault) is evident

3.2 Seismic event trigger

For the most part, mining-induced seismicity is triggered by blasting. However, the data suggested that there was no specific trigger for the MN3.5 event (i.e. blasting, drilling, filling, etc.). The event occurred while production holes were being measured and the stope had been drilled-off several days before. The neighbouring stope had been backfilled a month prior and stope blasting had not occurred for over three months. Prior to ME-250, the largest event in the block was a MN1.7 which occurred during production drilling several shifts prior to ME-250. Figure 9 shows the seismic trend (magnitude–time, in moment magnitude MW) for the sill pillar for roughly six months prior to the ME-250 event.

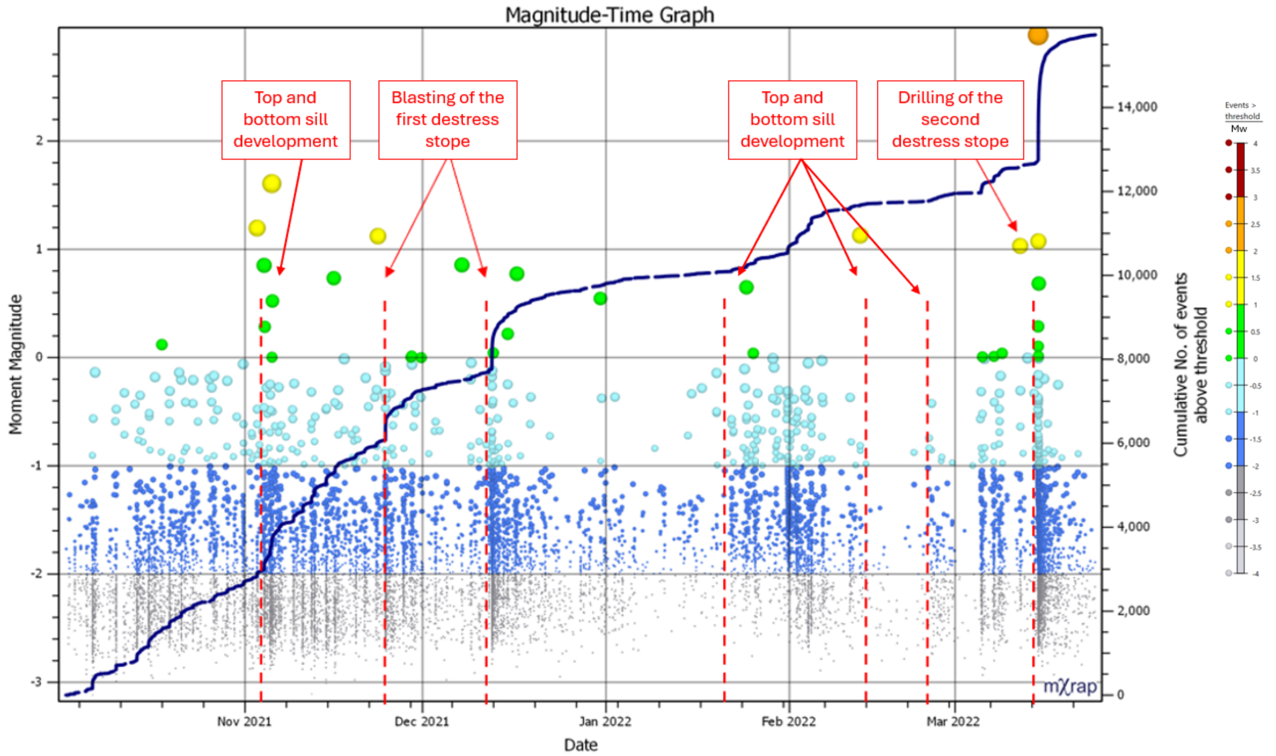


Figure 9 Magnitude-time relation (MW) showing the life of ore slot mining in 4945 Block 2. Key mining steps are highlighted including establishing the top and bottom sills, stope blasts and stope drilling. The ME-250 event is the large orange dot on the top right of the Figure (the largest event recorded in the orebody)

Figure 9 shows a seismic event trend where spikes in activity and large events are driven by key mining steps such as development, stope blasting or drilling. The challenge with the ME-250 event is that it was delayed, meaning there was no specific trigger and it occurred long after a blast. Additionally, the ME-250 fault structure was not known prior to the event. Delayed events are difficult to manage as a post blast re-entry protocol typically will not capture them. The primary tool to manage delayed events is ground support (once design measures are exhausted).

3.3 Damage mechanism

It is important to note that the worker was not injured during the ME-250 event as the enhanced ground support in the vicinity of the stope served its purpose. However, the MN3.5 event resulted in significant damage totalling roughly 900 t of combined rock and backfill from supported ground. The damage was observed to be caused by the large seismic waves passing through the sill pillar shaking the excavations.

Large seismic events typically cause damage in three primary mechanisms:

1. bulking of previously fractured ground

2. strainbursting driven ejection
3. ground motion driven shaking (Cai & Kaiser 2018).

Observations from the site investigation indicate that most of the damage occurred at a distance between 80 m and 120 m from the seismic source, and ground support performed well closer to the seismic source. Much of the damage was driven by 'shakedown' (shake-out or shake-down of previously fractured material). Figure 10 shows an isometric view of the 4945 Block 2 Sill Pillar highlighting the MN3.5 event location, post event micro seismicity, and key damage locations (drone scan images).

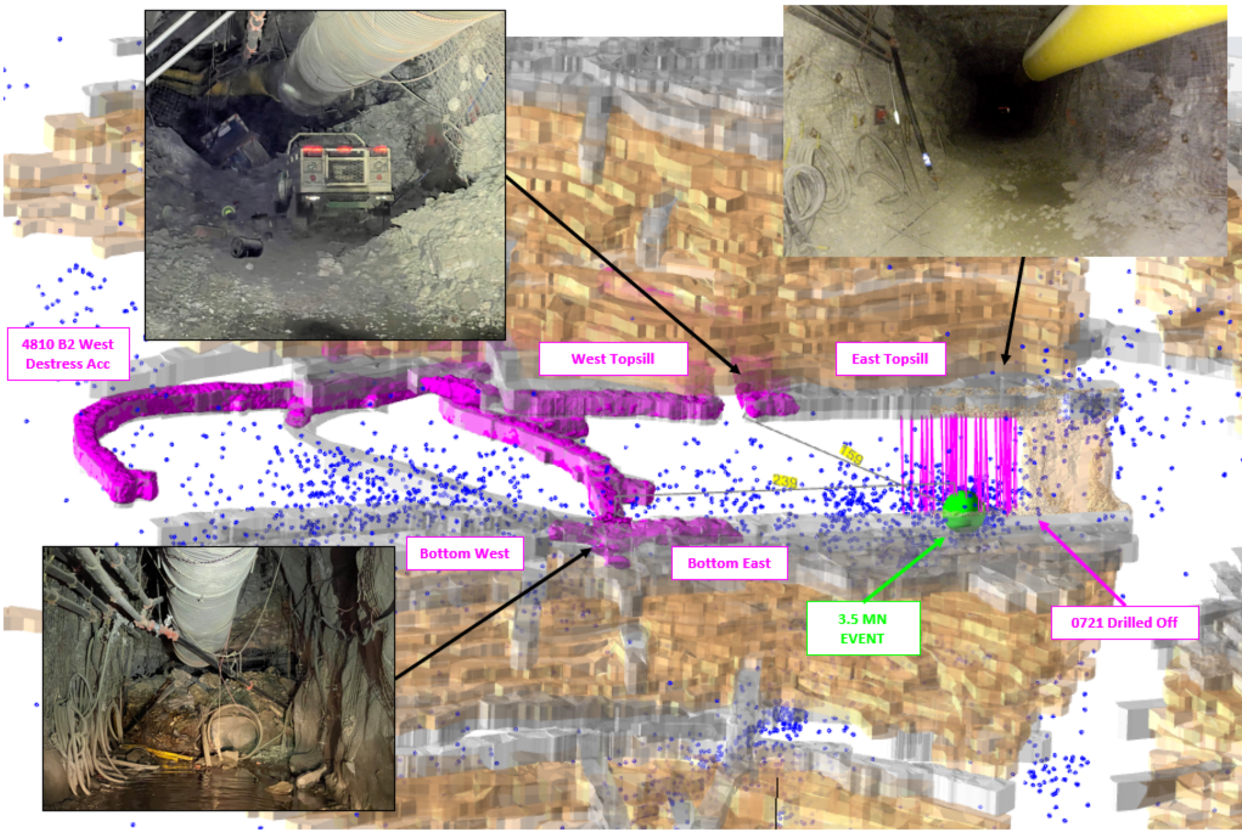


Figure 10 Long section looking North showing a simplified damage map of the 4945 Block 2 Sill Pillar post ME-250 rockburst

On the top level, floor heaving, wall bulking and shakedown of backfill was observed throughout the main access. Several backfill fences previously installed had been cracked, ejected, or had bulked/heaved. A remote production drilling stand was also affected by the rockburst damage (see top left photo in Figure 10). The remote drilling stand was placed roughly 80 m from the stope but was inadvertently in the area which was damaged by the seismic event. Remote drilling was being utilised for production drilling in the sill pillar as seismicity is often triggered by drilling. Remote drilling is an important control measure to keep workers away from high stress ground conditions.

In the bottom level of the sill pillar, failure was isolated to a main intersection (roughly 450 t) which was used to access the stope for mucking. Failure extended beyond the intersection support (3.6 m inflatable bolts) up to the ore lens contact; depth of failure of roughly 3.6 m. Seven shotcrete pillars had been constructed in the main intersection area to reduce its effective span and limited the extent of the failure. Additionally, in some damaged areas, visible corrosion on the support elements was evident suggesting the capacity of these supporting elements had been compromised. An immediate lesson learned was actioned to inspect all high seismic hazard areas and upgrade the ground support where insufficient length or corrosion was identified.

3.4 Key findings and recommendations

It is important to note that the details provided in this paper regarding ME-250 are only a summary of the complete rockburst investigation with only some of the pertinent data presented. The key findings are summarised below:

- Seismic event mechanism:
  - The MN3.5 seismic event is a fault slip event on a previously unknown second order fault.
  - The event was delayed and was not triggered by blasting. Drilling/cleaning the raise was ongoing around the time of the event.
- Primary damage mechanism was seismic shakedown.
- Notable recommendations:
  - Improve the mines understanding of major geological features.
  - Implement a ground support preventative maintenance program.
  - Implement an analysis technique for the classification of delayed seismic events.
  - Implement a formal selection process for remote stand locations.
  - Improve the process of developing seismic hazard maps.
  - Improve the design and planning process for sill pillar mining.

3.5 Implementation of key findings and recommendations

The most critical aspect of an investigation is the identification and implementation of lessons learned and recommendations. For the ME-250 event, recommendations were focused on design processes as the design did not fully consider this magnitude of event or failure mechanism. This section summarises several design processes which were implemented as learnings from the event.

3.5.1 Structural model

One of the key conclusions from the investigation was that a major structure (not previously known or identified) was the source mechanism for the event. As a result, the mine assembled a team to re-build the structural model and put processes in place to maintain the structural model with sufficient 'resolution' to capture second order faults and structures. The goal is to have a structural model and workflow that is predictive, such that problematic structures are detected early and made available to the engineering teams as soon as possible. The team constructed a new mine-wide structural model (Kruse 2024) using all available data including diamond drill information and mapping. This model is now completed and available for mine staff to maintain and use for design. Structural modelling best practice guidelines and training for mine staff were also part of this work.

3.5.2 Ground support preventative maintenance program

The rockburst investigation described in this paper identified a need to improve the monitoring and replacement guidelines for ground support. A ground support preventative maintenance program (GSPMP) was developed to guide the design and monitoring of ground support, and to ensure that the installed ground support remains adequate for the ground conditions. The GSPMP consists of the following components:

- Ground support design basis to document: damage mechanisms, first principal calculations, and maintenance assessment guidelines.
- Excavation design process to document the mine design process and ground support communication process.

- Ground control inspection program to formalise an inspection guidebook ('how-to'), unusual ground condition trigger action response plan (TARP), and ground support corrosion TARP.
- Maintenance program to standardise state of ground support maps and the ground support upgrade process.

A notable aspect of this program is the standardisation of ground support maps. To formally document support in place, conditions of ground support and ground conditions throughout the mine. Ground support maps consist of maintaining snapshot in time plans of mine levels to track changes in ground conditions and ground support. The maps are required for all active mining levels and critical life of mine infrastructure (production areas, shops, muck circuit) and are updated annually or when a significant change is required to the mine plan. The maps serve as a history of all previously completed ground support work and maintenance (upgrades or rehabilitation). A guidebook was developed to serve as a minimum standard for the creation of these maps. Currently, maps are maintained in the mines CAD system. Figure 11 below provides an example for state of support maps.

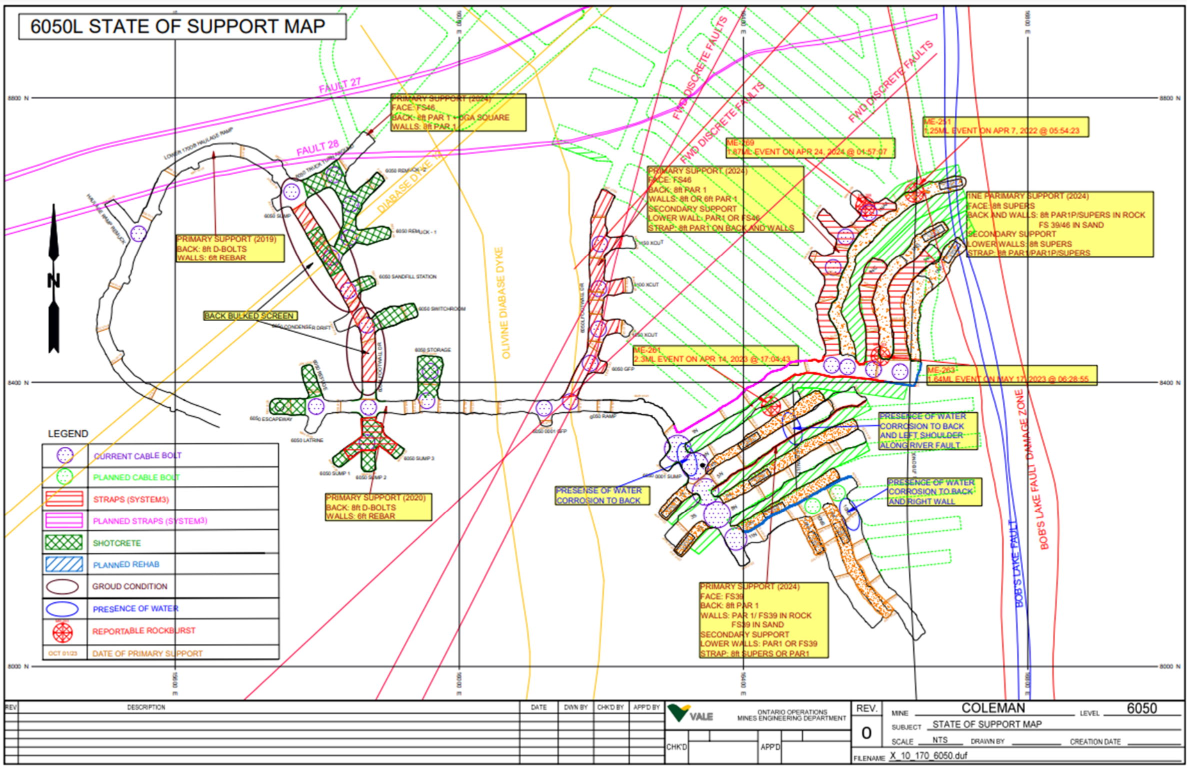


Figure 11 Ground support maps example

3.5.3 Classification of delayed seismic events

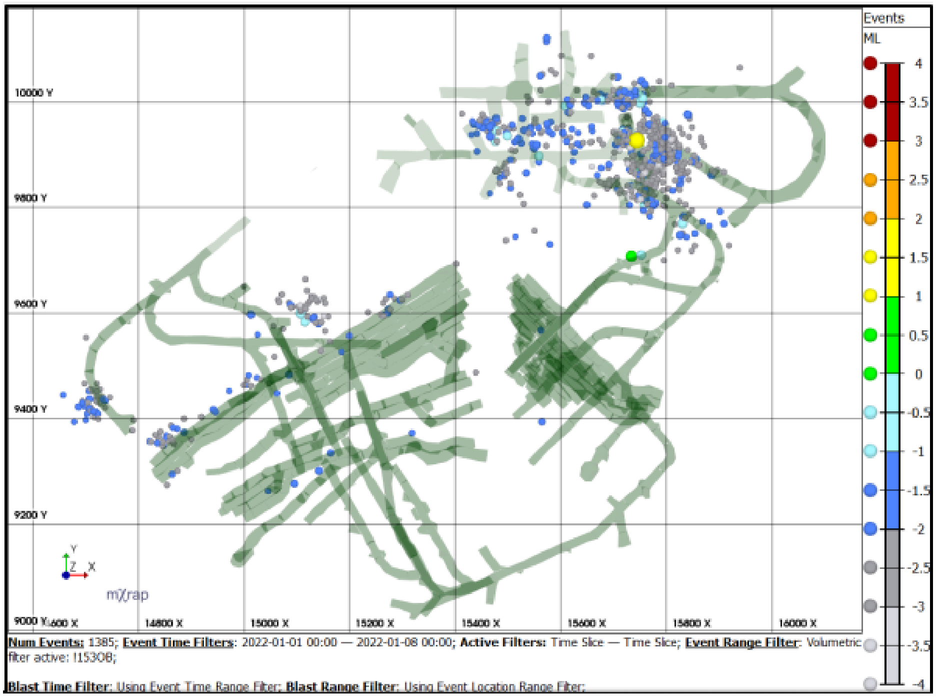
The ME-250 rockburst highlighted a need for an additional tool to assess and classify delayed type seismic events. For simplicity, Type A seismic events are those which occur as part of seismic induced stress change and with blasting. Type B or delayed seismic events are those which do not occur directly after blasting and occur distant to mining-induced stress change (Richardson & Jordan 2002).

A project was initiated onsite to develop an analysis tool which quantitatively screen the seismic events into Type A and B events. Previous work by Brown (2018) was used to develop an in-house mXrap application (Camball 2024) which filters events based on distance and time parameters. This paper will not detail specifics of the analysis technique, however; the aim is to provide insight into what is now available for practitioners.

Distance and time-based parameters consider discrete mine blasts and grid based seismic response clusters to calculate four main parameters: time after blast, distance to blast, time between events, and distance to (cluster) centroid. The sum of the normalised parameters serves as a single value indicator between 0 to 4

(0 representing a pure Type A event and 4 representing a pure Type B event). Distance–time parameters are simplistic and reliable as there is generally little to no error associated with seismic event time, and event location error is routinely quantified for individual events. Using only these independent seismic source parameters ensures error is minimised and cannot propagate through multi-stage analysis.

Figure 12 is an example of typical seismic analysis performed using this novel application which was developed inside the mXrap software platform (Harris & Wesseloo 2015).



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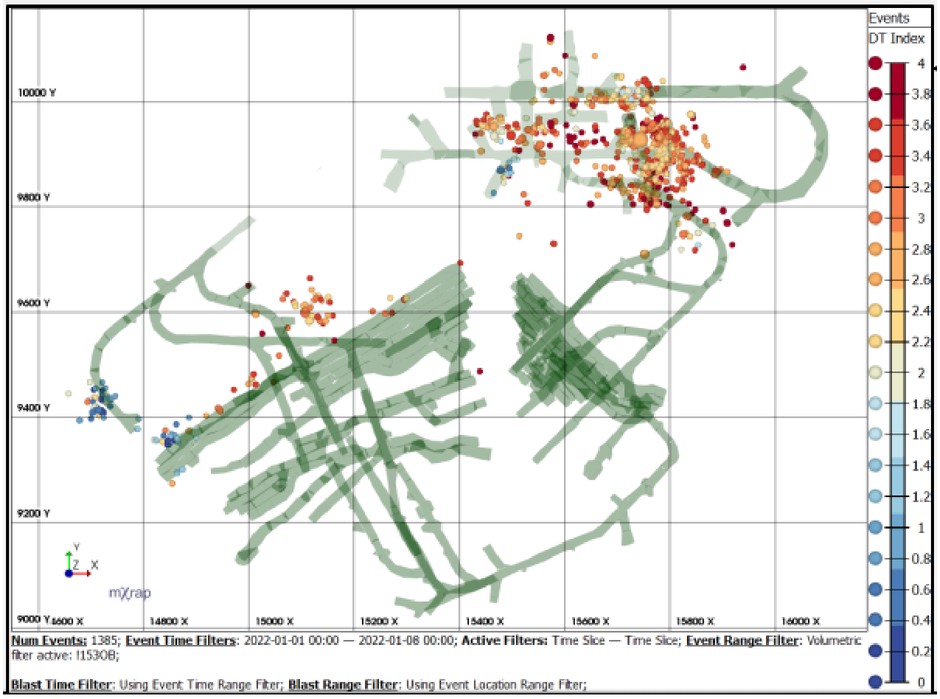


(b)

Figure 12 Plan view of 4945 Level. (a) Events coloured by magnitude; (b) Output from the distance–time index (DTI) application built in the mXrap platform, events coloured by DTI

Figure 12a shows seismic events for a given period coloured by magnitude and Figure 12b the distance–time index (DTI). Two large clusters (sill pillar and abutment events) in Figure 12b have relatively high DTI value, while small clusters in Figure 12a (development heading) exhibit lower DTI values. These parameters explicitly highlight Type B events throughout mining environments, making them useful for proactively identifying areas prone to delayed seismic events.

3.5.4 Remote stand location design

A remote production drill stand was installed and used in a location which was subject to rockburst damage during the ME-250 rockburst. As a result, remote stand placement design was formalised into a standard procedure. Key guidelines for remote stand placement are listed below:

- Where high stress is anticipated in the stope (i.e. sill pillars, leading abutment stopes, and/or seismically active structures) remote drilling and extended mucking distances are utilised to keep the workers outside of the stress front. Seismic analysis, review of numerical models and a site visit or sound knowledge of the area is a prerequisite for this task.
- Ground control ensures ground support is prescribed to suit the current and anticipated future ground conditions (i.e. dynamic support in high stress conditions) in the remote stand location.
- Communication of the remote stand location and site visits are also part of the guideline.

3.5.5 Seismic hazard maps

A process was formalised to outline the minimum requirements for seismic hazard maps. The program requires that seismic hazard is evaluated, documented, and communicated for all mine levels on an ongoing routine basis. The general process is to utilise all seismicity related data to determine a hazard level for a mining area. For this minimum standard, a qualitative methodology has been proposed. Hazard is defined in terms of a region having low, medium, or high likelihood of producing large seismic events (MN > 2.0) within the period being considered. A formal assessment and update of hazard maps is completed annually at a minimum as part of the Ground Control Management Plan update. The developed ranking criteria is shown in Figure 13.

MINING BLOCK SEISMIC HAZARD MAP WORKSHEET

Mining Practice	Geology	Seismicity	Rockbursting	Observations/Experience	Modelling (Stress Levels)	Rating	
No local or regional pillars, mining sequence is simple. Low exposure mining method (bulk down-holes, remote mucking/drilling) 1	No major structures are present in the zone and the rockmass characteristics are consistent. 1	Seismicity levels low. Largest magnitude event < ML 1.0 and blasting does not generate clustering of seismicity 1	No rockbursts experienced 1	Underground observation show no signs of stress, no ground deformation. 1	Numerical modelling shows relatively low stress conditions present as mining progress or mining in shadowed or yeidled ground. (Dev Stress < 0.39) 1	6 to 10	Low
Normal mining geometry. Moderate exposure mining (two-boom C&F, uppers) 2	Major structures are present in the zone and the rockmass properties vary slightly 2	Seismicity levels moderate. Largest magnitude event < ML 2.0 and blasting generates clustering of seismicity 2	Minor rockbursting experienced 2	Underground observation show minor major signs of stress, ground deformation 2	Numerical modelling shows relatively moderate stress conditions present as mining progresses. (Dev Stress ~ 0.4 to 0.69) 2	11 to 13	Moderate
Mining geometry is complex with local or regional pillars. High exposure mining (muckpile) 3	Several active structures are present and there is a large contrast in rockmass properties. 3	Seismicity levels high. Largest magnitude event > 2.0 ML and blasting generates significant clustering of seismicity 3	Severe rockbursting experienced 3	Underground observation show major signs of stress, ground deformation. 3	Numerical modelling shows relatively high stress conditions present as mining progresses. Mining on a high stress abutment or loaded pillar. (Dev Stress > 0.7) 3	14 to 18	High

One description selected per column, scores shown are added togethor which will give a final hazard rating between 6 and 18

Figure 13 In-house seismic hazard worksheet used for the creation of hazard maps

The hazard ranking exercise is completed for each zone on individual levels. This exercise is useful for mine staff to routinely analyse, document and communicate the hazard levels and control measures for all areas of the mine. Figure 14 is an example of an in-house seismic hazard map for a mining level.

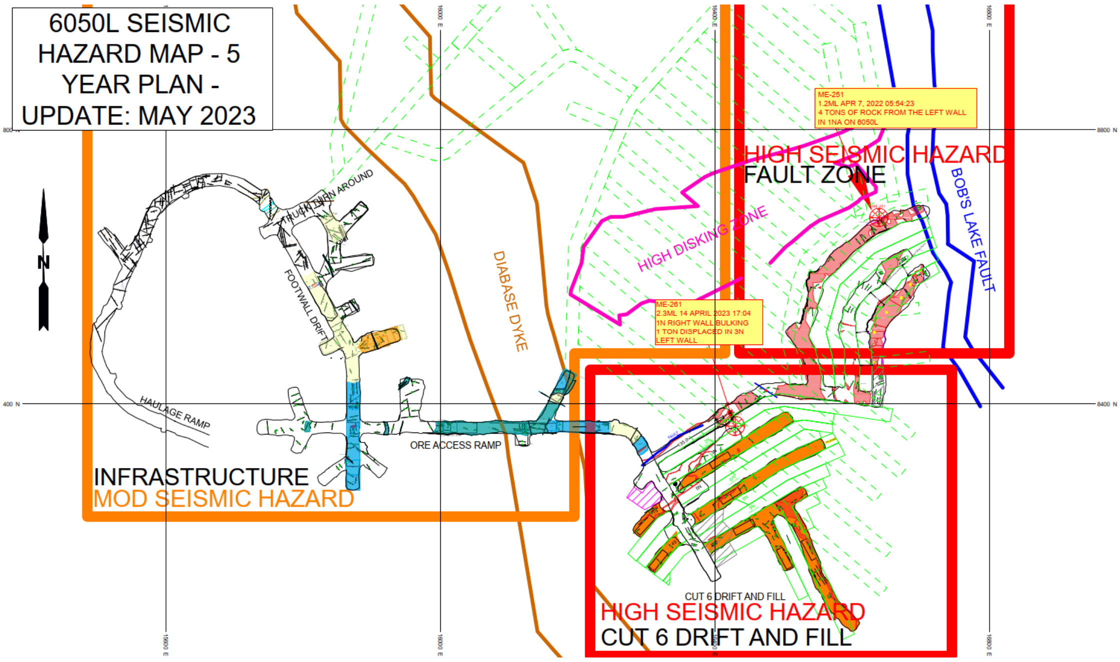


Figure 14 Seismic hazard map for a mining level. Existing excavations shown, as well as long-term development in green. Seismic hazard is indicated by the coloured boxes

3.5.6 Sill pillar design process

Although a formal design was completed for the 4945 Block 2 Sill Pillar, one of the actions resulting from the ME-250 investigation was the development of a process which outlines the technical requirements to develop a sill pillar extraction strategy. The process (Hossack 2023) covers the steps to be followed to develop a sill pillar extraction strategy at Vale Base Metals operations. The process formalises the sill pillar extraction design process into a project which includes the following key components:

1. Develop scope of work, clear objectives, deliverables, and schedule to carry out the work.
2. Complete data gap analysis.
3. Conduct data collection program.
4. Develop geotechnical model (rock mass, structural, geological, hydrogeological).
5. Determine the optimum pillar thickness or current loading condition of the sill pillar.
6. Determine extraction strategies based on industry accepted methodologies.
7. Apply a risk level approach to each extraction strategy.
8. Conduct multi-criteria analysis to select preferred option.
9. Conduct a mid-point review.
10. Complete detailed engineering: loading conditions, seismic hazard, determine ground support requirements including reconditioning, finalise mining geometry and sequence, finalise additional controls, TARPs.
11. Carry out final review.

4 Path forward: 4945 Block 2 Sill Pillar

The independent investigation team concluded that the ME-250 event was an outlier and could not have been anticipated. The team also concluded that the mining method was acceptable, but several key aspects could be improved on, such as the understanding of geological features in the sill pillar and ground support robustness.

Rehabilitation of affected areas was completed, and the design was revisited to meet Vale Base Metal's new sill pillar design standard. The following are highlights from the updated sill pillar package.

4.1 Structural investigation

A targeted diamond drilling program was completed to better understand the ME-250 fault and test for other major structures in the sill pillar. The drilling confirmed and defined the ME-250 fault. The primary conclusion from the structural analysis is that the ME-250 fault was identified (post-MN3.5 event) by a small zone of broken ground (damaged from the seismic event). The zone is characterised by multiple slip surfaces (slip along fractures) containing chlorite alteration (pink potassic, epidote and chlorite alteration). Figure 15 summarises the results of the structural drilling program.

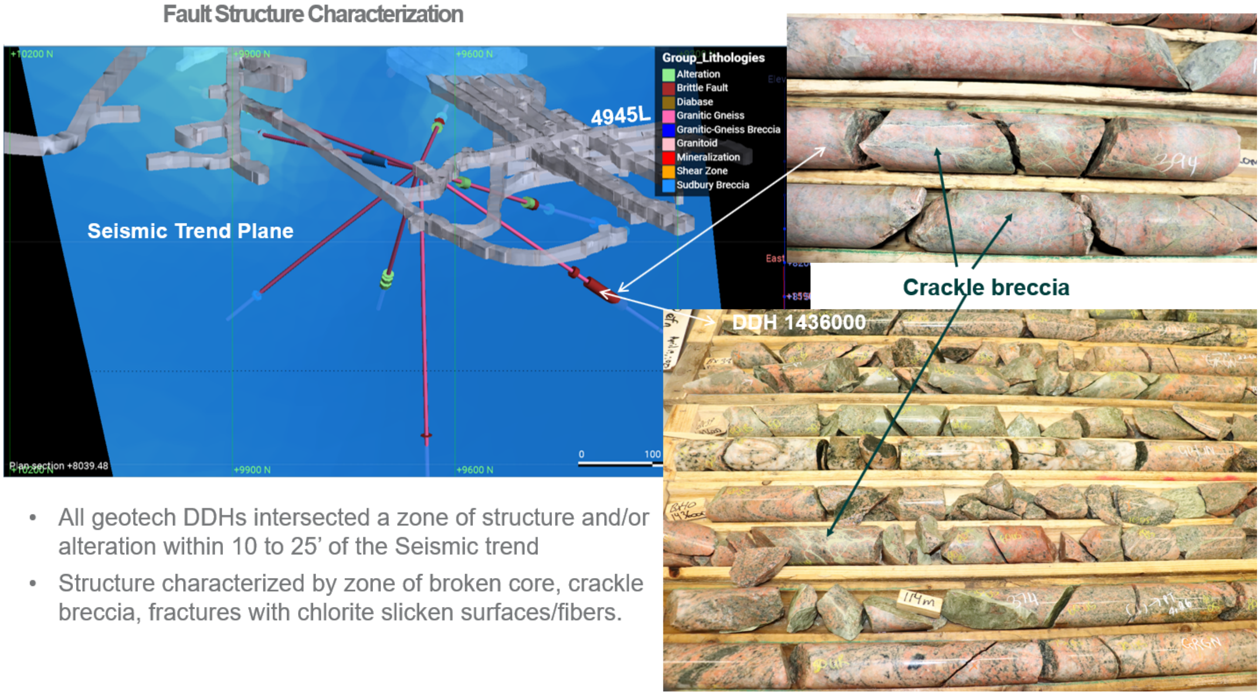


Figure 15 Isometric view of 4945 Block 2 footwall showing completed geotechnical drilling locations along with observations completed by the structural geology team

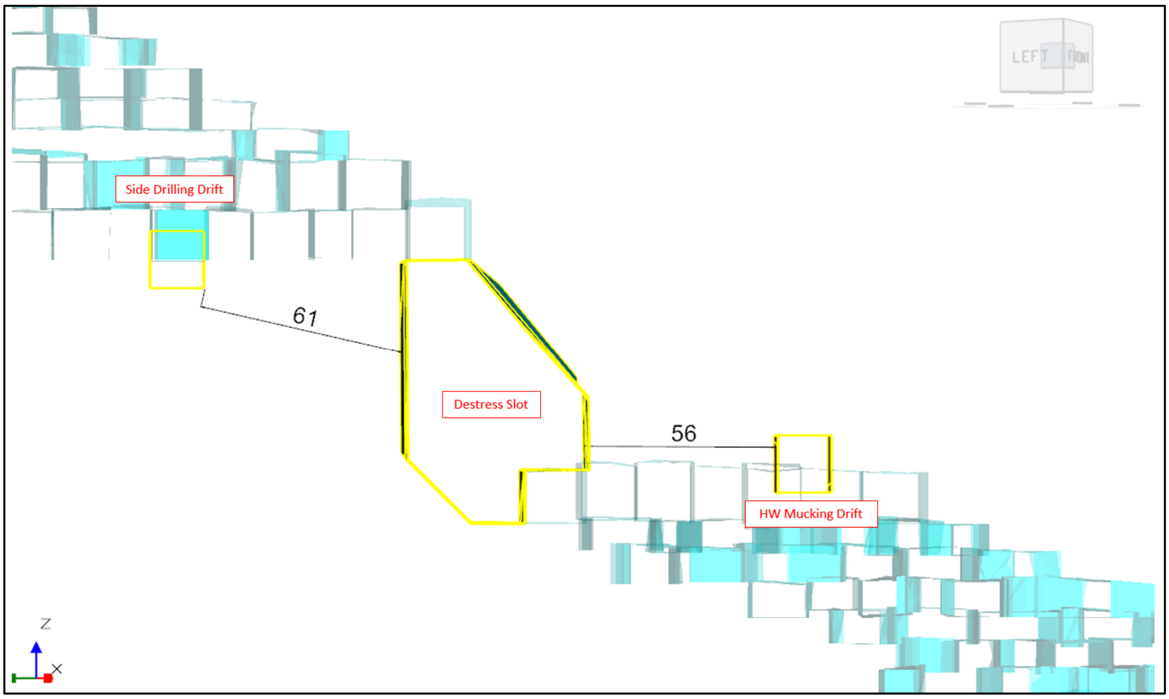
Additional geotechnical drilling was completed to fill gaps in the current drill coverage and investigate if any additional structures are present in the sill pillar.

4.2 Detailed engineering: updated sill pillar design

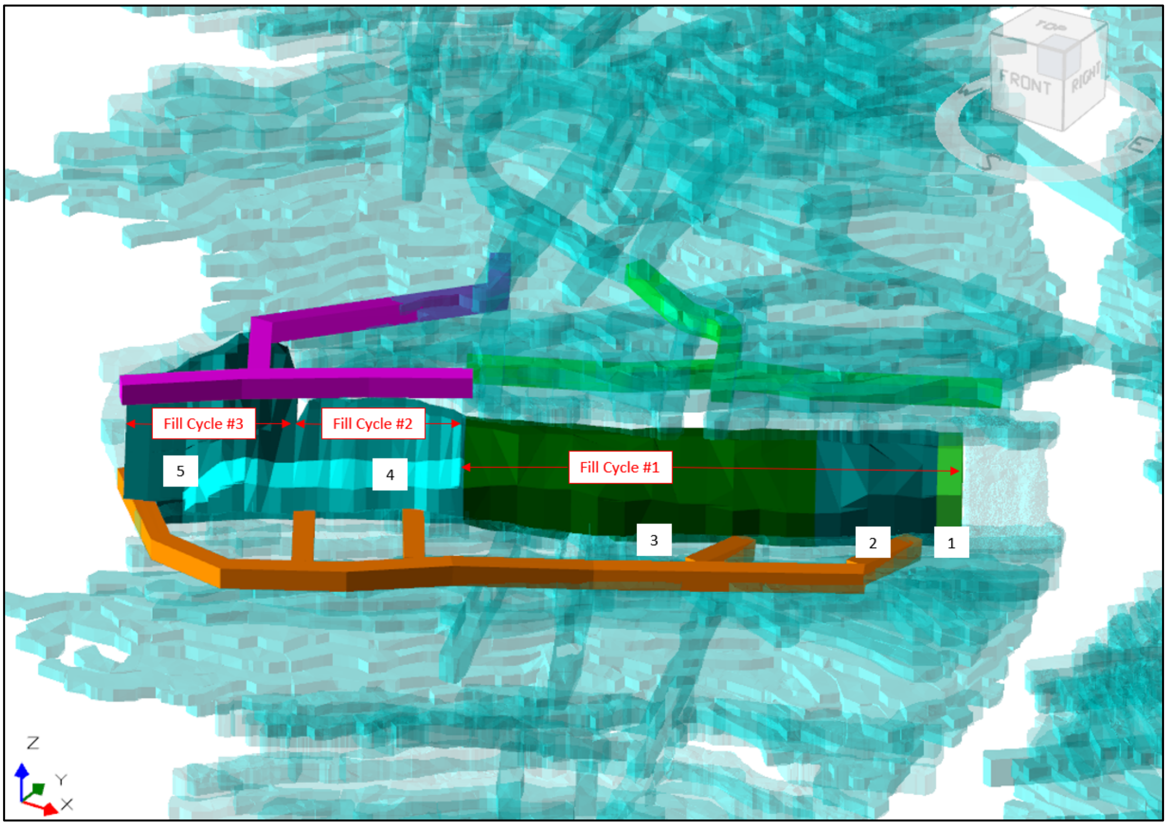
Through the process of determining and geotechnically risk ranking possible new extraction strategies, the mine design premise and extraction strategy of this sill pillar has been revised to be as follows:

- New designs must account for a similar magnitude seismic event to the ME-250 event.
- The new design aims to remove the development from the high stress pillar where possible and still follow the shadowing method to cut-off stress from the sill pillar.
- New designs aim to minimise intersections.
- Ground support upgrades completed throughout the sill, not just the pillar core area. Long support: cable bolting, resin grouted support for corrosion resistance, upgrade to 4-gauge mesh.

The current methodology is to side-drill from the footwall of the orebody outside of the sill pillar core. Mucking will be complete via a new hanging wall mucking drive, also outside of the pillar core. Figure 16 shows the updated design for the 4945 Block 2 Sill Pillar.



(a)



(b)

Figure 16 4945 Block 2 updated design. (a) Main slot mining configuration, with side drilling drift and hanging wall mucking access shown in yellow. Filled cuts shown in blue; (b) Iso-view 4945 Block 2 top sill, bottom sill development and de-stress slot design. Blast numbers are indicated along with planned fill cycles

4.2.1 Drift placement

A new drill drift will be re-positioned under the fill on the footwall of the orebody. The goal is to reduce worker exposure to the pillar core. For the main part of the sill (~two-thirds of it), production drilling will utilise a side drilling methodology (drift distance from the pillar core is determined by longest practical drill reach). As the ore flattens on the abutment, a hanging wall drill drift has been designed which will allow for downhole recovery. The topsill will ramp up above the filled cuts to keep the drill drift outside of the pillar abutment stress front. The design includes mucking points from the hanging wall side on the bottom sill to avoid the pillar core. Footwall crosscuts were not recommended due to the requirement to place them below the pillar core. For the abutment, a new hanging wall access will be driven through the filled stopes to access the remaining ore from a stress shadow.

4.2.2 Other design inputs and control measures

The slot will be mined with the fewest possible number of blasts, to de-stress the sill as quickly as possible. The goal is to reduce exposure and, in an attempt, to trigger any large seismic events with blasting. Extended seismic stand-off re-entry times will continue to be utilised for development and production blasting in the sill pillar. A stress cell array has been installed to monitor the stress front as the sill pillar stopes are mined. The purpose of this monitoring is to monitor the stress front and aid with design confirmation (load/unloading and modelling calibration). Furthermore, to reduce worker exposure, the mine is working to implement tele-remote mucking and drilling for this sill pillar.

5 Conclusion

This paper gives a summary of a MN3.5 fault slip seismic event which occurred while completing mining of the 4945 Block 2 Sill Pillar at Coleman Mine. Key lessons learned and the path forward for the sill pillar have been presented.

It is essential to understand that deep mining involves some uncertainty and risk, and it should be recognised by industry practitioners that it is extremely difficult to anticipate seismic events such as the ME-250 event, when there are no clear indicators from seismic or structural data.

The purpose of publishing this information is to share the lessons learned from ME-250 and how they have been applied to improve designs and process.

Acknowledgement

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