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Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic event: part 1 – the investigation

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Abstract

A MN3.7 seismic event occurred on 30 October 2020, at Westwood mine. Following this event, the entire mine production was halted and the mine was put under care and maintenance. This decision was made to focus on understanding the mechanism of the event and to identify areas with potentially similar conditions. The paper aims to present the background information that was available prior to the event. Subsequently, the investigations were carried out to understand the mechanism of the seismic event. The investigations include geological, structural and geotechnical model updates, advanced seismic analyses, numerical stress modelling, integrated rockburst hazard assessment, as well as a complete review of the dynamic ground support standards of the mine.

Keywords: *seismic risk, rockburst, stress modelling, rock mass characterisation, damage mapping, seismic Hazard Map.*

This paper is part of a larger paper made of two papers. Paper 1 Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic events: part 1 – the investigation (this paper), addresses the investigation of rock mass behaviour characterisation. Paper 2 Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic event: part 2 – the mitigation plan, addresses the implementation of a mitigation plan.

1 Introduction

The occurrence of a major seismic event is very critical for a mine. Usually, such an event can have serious consequences on its operations, as experienced at the Westwood mine, where a MN3.7 seismic event occurred on 30 October 2020. Following this event, all mine production was suspended to focus on understanding the event's mechanism and identifying areas with potentially similar conditions.

A good understanding of the geotechnical behaviour of the rock mass was necessary to continue operations. Thus, a rock mass characterisation campaign was initiated at the Westwood mine after this major event. To successfully carry out this campaign, a geotechnical strategy was implemented to better characterise the rock mass, including:

- the investigations and updates to geological, structural, and geotechnical models
- advanced seismic analyses
- numerical stress modelling
- integrated rock burst hazard assessment
- a comprehensive review of the mine's dynamic ground support standards.

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Additionally, a detailed risk register was created to identify ground control-related hazards and establish a mitigation plan, covering risk identification, existing mitigation measures, current hazard levels, proposed mitigation measures, and residual hazard levels. For the geotechnical model's establishment**,** the following parameters were analysed:

- like alteration
- disking
- mechanical properties
- geochemistry
- Rock quality designation (RQD) and geological strength index (GSI) with regards to the historical major seismic events.

This analysis allowed for the identification of seismic domains.

Furthermore, a ground assessment was performed doing a systematic damage mapping of all existing underground openings. An in-depth seismic analysis was conducted to understand the source mechanism of all major events that occurred at the mine, including the cluster of events that occurred close in time, as well as seismic hazard maps; which consist of identification of seismically active faults as well as the probability of occurrence from past seismic events.

Finally, stress modelling based on re-run numerical stress models with Beck Engineering and updated lithology and structure models, to understand the impact of the mine sequence on mine opening stability and seismic potential, were performed.

All of this information helps to determine strategic and tactic measures to reduce the seismic risk at Westwood. These measures include:

- the design of an adequate ground support system
- using a machine-learning algorithm with Mira Geoscience allows identification of variables that affect rock burst potential
- enhancement of the precision of the seismic system.

The current and residual risk of personnel exposure has been assessed using a risk management process (risk register with mitigation measures). A detailed plan has been established to deploy the mitigation measures, then, a strategy was developed to thoroughly investigate the mine's seismic and geotechnical behaviours and develop mitigation to safely reopen the mine.

The following sections briefly introduce the Westwood mine, followed by the developed investigation methodology and the results obtained.

2 General review of Westwood mine

2.1 Localisation/geology

The Westwood mine is located approximately 40 km east of the city of Rouyn-Noranda, in the Doyon-Bousquet-LaRonde mining district (Figure 1a). Gold production at the Westwood mine started in March 2013 and the first ingot was poured on 27 March 2013. The official commercial production started on 1 July 2014. The deposit is composed of three mineralised corridors, consisting of numerous lenses. Continuous and discontinuous lenses extend over 2,000 m from east to west, by 600 m from north to south and extend to over 1,800 m in depth (Figure 1b).

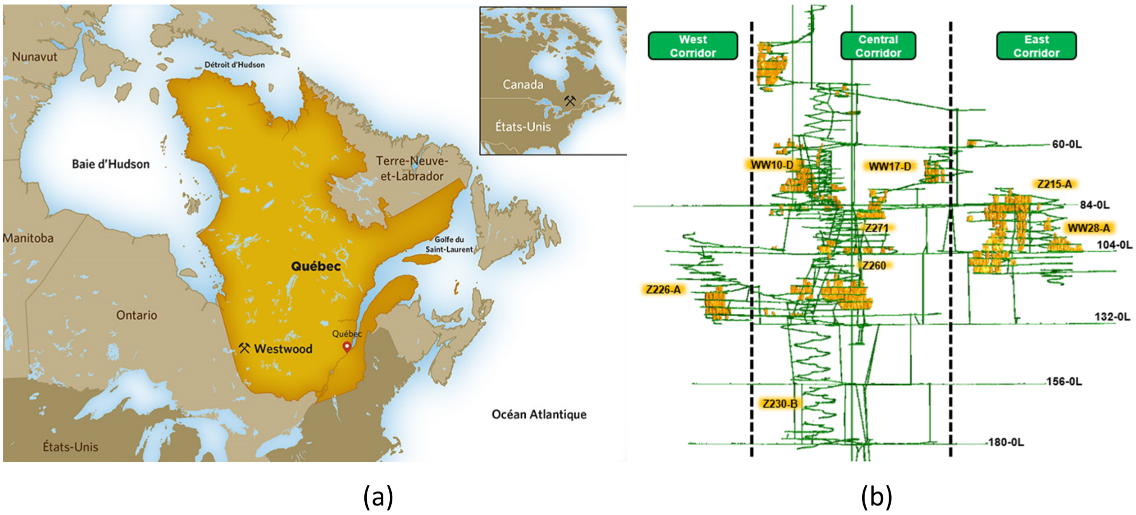


Figure 1 Westwood mine location within the province of Quebec, Canada

2.2 Geology of the Westwood mine

The geology of the Westwood mine consists of six main units: basalts, rhyolite sills, intermediate felsic and mafic volcanic rocks, andesite to dacite or rhyodacite dykes, as well as felsic lapilli or block rocks. The basalts (U1) are very hard, fragile, and moderately seismic when intersecting unit 2. There are massive gabbro dykes (U4.4.1) that are very hard and seismic, capable of generating significant events. The felsic rhyolitic sills (U2) are soft with more altered zones/planes, exhibiting slightly plastic and anisotropic behaviour. These sills can generate seismicity when alternating with U1. Regarding the intermediate to mafic volcanic rocks (U3), these rocks are hard to very hard, fragile, heterogeneous, and can generate seismicity, reacting quickly if not combined with other structures. The alternation of andesite to dacite/rhyodacite to rhyolite/basalt to andesitic basalt/gabbro is an alternation of convergent to highly convergent plastic zones, soft, moderately hard to very hard, and fragile. Extremely hard and fragile zones are gabbro and andesite dykes, which are highly seismic under high stress, especially when adjacent to subunit 4.3 alternating with unit 3. The contact between U3 and U4 presents a seismic transition zone that becomes extremely seismic when alternating with U4.2.0 (andesite/dacite dyke). The intermediate to mafic volcanic rocks (U5) are generally soft to moderately hard and sometimes altered with sericite and chlorite, containing U4.4.1 and U5.1.3 dykes that are seismic. The last unit (U6) primarily consists of felsic lapilli or block rocks with low seismic susceptibility.

According to the seismic history of the Westwood mine, the U4.2.0/U4.4.1/5.1.3 dykes and the contact between units U3 and U4 (U3-U4 transition zone) represent high seismic potential areas.

Structurally, the faults at the Westwood mine are classified into three categories: east–west, oblique, and north–south. Currently, 36 faults are modelled at the mine scale, each with different seismic potential.

The diversity of faults and units makes the rock mass at the Westwood mine very complex. A more advanced characterisation of the rock mass is carried out in the GeoSeismic Strategy of the mine, which is the subject of another article.

2.3 Mine layout description

The mining infrastructure for zone Z226 is accessed via ramp west #3 between levels 104-01 and 132-04, and through ramp west #1 (the main ramp) between levels 132-04 and 132-01. From level 132-01, ramp 133 is being developed to extend ramp west #3 to greater depths. The Z226 lens will be mined between levels 132-01 and 104-01. The active and mined levels currently range between 132-01 and 132-06 (as illustrated in Figure 2), where the mined stopes are shown in pink and the planned stopes are shown in purple. Mining production in the Z226 lens started at level 132-01 and progressed upwards. The specific stopes that were mined are detailed in the longitudinal section shown in Figure 3, were the mining method before the seismic event was primary-secondary, with a leading stope.

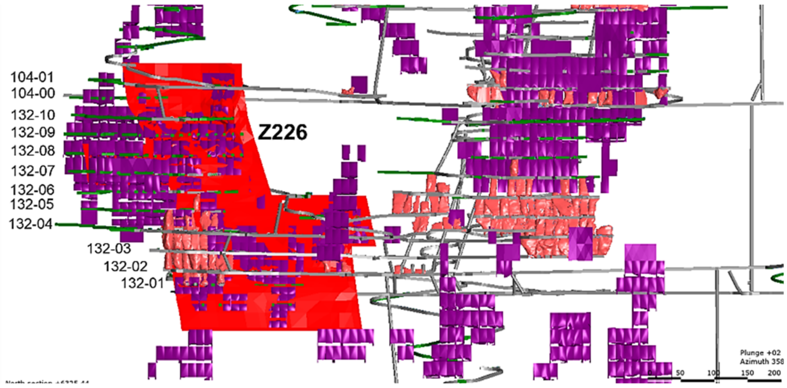


Figure 2 Mining infrastructure in the Z226 area

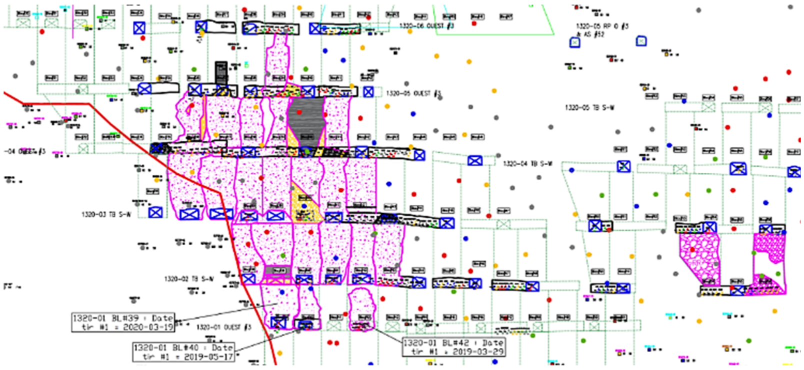


Figure 3 Longitudinal view north: mined stopes in the Z226 lense

2.4 Previous major seismic events and rockburst at Westwood mine

Westwood mine suffered since the early stage of development from a series of major seismic events. The first major seismic events occurred in 2013, before the commercial production has started in 2014. Table 1 summarises these major events and the long section of Figure 4 shows the distribution of the seismic events since 2013. This information was provided from internal company reports.

Table 1 Overview of the major seismic events that caused significant damage

Year	Location	Date	Magnitude	
			Moment (MW)	Nuttli (MN)
2020	132-03/04/05	2020-10-30	–	+3.7
2018	132-10 PS-73/74776/78	2018-12-22	–	+3.0
2018	132-11 TB-EST	2018-11-07	+2.0	3.0
2017	132-02 TB-EST	2017-09-23	+1.3	–
2015	084-01 and 104-06/08	2015-01-22	+1.6 +1.4	2.8 2.7
2015	104-02/03/04/06/08	2015-05-26 2015-05-27	2.1 and 1.8 1.9	+3.2 and 2.7 2.4
2014	104-02	2014-12-12 2014-12-29	1.4 1.1	1.8 N/A
2014	104-02	–	–	3.0
2013	104-02/03/04/06/08	2013-08-31	1.4 2.4	2.2 3.0

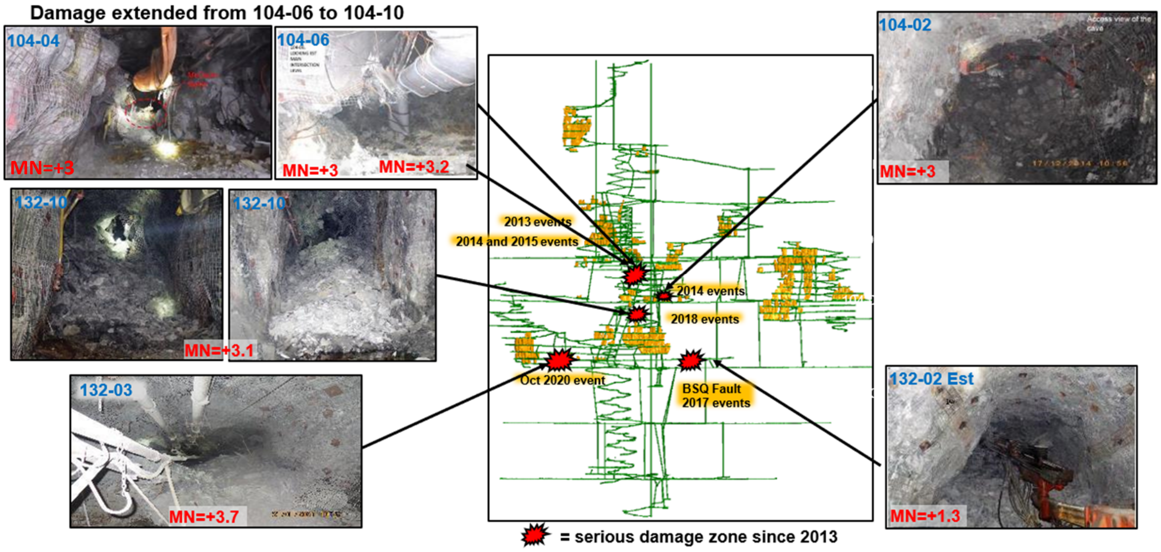


Figure 4 Longitudinal view north of the distribution of the seismic events since 2013

2.5 Installed ground support (prior to 30 October 2020)

The heavily damaged zone caused by the seismic event was initially supported by so called (standard #5). The ground support for standard #5 composed of: H7's (Split set – 1.98 m (6'6") – 35 mm + rebar bolt with forged head – 1.9 m (6'2") – 20 mm) in the walls on a 1.2 × 1.2 m pattern, with three horizontal bands of screen type #0 spaced 1.2 m vertically. H7's are also installed in a staggered pattern (in the centroids of the pattern). The pattern starts at 0.6 m off the floor. Along the back, R6's (rebar bolts - 1.9 m (6'2") – 20 mm) are installed on a 1.2 × 1.2 m pattern. RB2's (mechanically anchored bolts – 0.6 m (2') – 16 mm) are installed in a staggered pattern (in the centroids of the pattern). Generally, nine cemented and tensioned 5 m cables are installed in the intersections and the pillars are supported using the pillar support standard. Over the months and years following the initial support installation, additional reinforcements were added. The most notable section that was supported is on the 132-02 TB SW level between PS#55 and PS#51. The north wall was reinforced with a 1.8 × 1.8 m pattern of 5m and 10 m cables between April and May 2016. Because of increase convergence, this wall was later purged and supported with standard #5 ground support, and further reinforced with cables in February and March 2018. During this time, a section of the south wall was also cabled. Following the purge, 10-foot rebars were installed to the back. Other zones in the affected sector of level 132-02 TB SW were subjected to cable lacing and received shotcrete on the pillars.

2.6 Historical design criterion (Z226)

The following information is taken from interna company reports. Geotechnical knowledge at the Westwood mine has significantly evolved since commercial production began in 2014. This evolution has been marked by multiple episodes of major seismic events (Table 1 and Figure 1) that either forced changes in established paradigms or initiated technical investigations, enhancing the geotechnical team's experience and knowledge. The design process of the west #3 area, where the October 30th event occurred, followed a similar path.

The Westwood mine experienced two major rockbursts in January and May 2015 (Table 1), causing severe damage to infrastructure and rendering significant portions of the orebody reserves inaccessible. Rapid development of new production fronts was necessary to compensate, and the Z226 ore lens became a targeted opportunity. Therefore, it is important to assess the initial design in this context.

Sublevel spacing for the entire area was set at 28 m from floor to floor (24 m of rock pillar). This spacing complied with external recommendations following the August 2013 rockburst and preliminary recommendations from the May 2015 rockburst (Table 1).

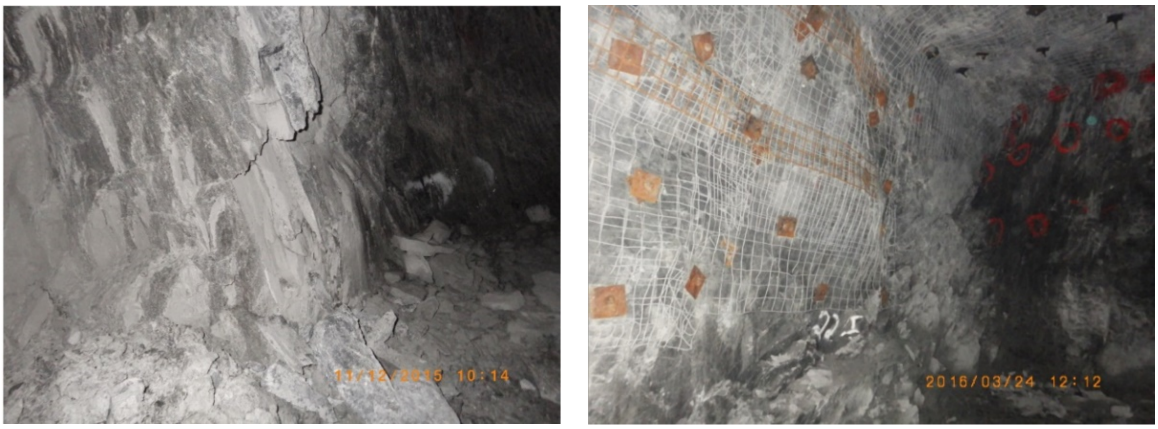
The drawpoints were designed in a ‘hockey stick’ configuration, commonly used in other areas of the mine. This design is a compromise between a full transverse design, which requires extensive horizontal development, and a longitudinal design, which demands access in the ore plane that remains open and safe for a long time. Another advantage of the ‘hockey stick’ design is the ability to maintain larger pillars between drawpoints compared to a fully transverse design. However, this design reduces flexibility in the mining sequence compared to transverse access and creates challenges in mucking the stope, as the scoop is often in a half-turned position.

Since the western extent of the mineralised zone was not fully known when development started in 2015–2016, it was decided to mine the eastern portion first while development continued westward. This sequence offered significant economic advantages by allowing production to start almost immediately but exposed adjacent drives to high stress.

Based on the available information at the time of design, the decision was made to access the Z226 orebody through the hanging wall. This approach aimed to avoid the strong convergence anticipated in east–west development within the unit 4 footwall rock. The hanging wall rock mass, unit 5, was considered to perform better in terms of convergence and posed a limited seismic risk. These hypotheses and decisions were based on experiences from the east side of the Bousquet Fault above the 104-00 level. Some convergence was still expected in the planned east–west excavations. Therefore, the two strongest ground support patterns used at the time were recommended in the early approval document (2015-12-18) by the ground control team. It is noteworthy that approximately 60 m of development on 132-02 had already been completed before the approval document was finalised.

Movement of the east–west drive walls and the soft ground behaviour of the U5 rock mass were observed early in the development process. Evidence of this movement was noted as early as November 2015, as shown in Figure 5a. Development was stopped in order to proceed with the upgrade and only resumed in January 2016. Failure to rapidly install proper ground support after the development blast proved to be an important factor for the drive performance. It was noticed, non-compliance to ground support standards was a generalised problem in this section of the mine. In that specific area it amplified the convergence problem. As development progressed toward the west, conditions did not improve and ground movement could be seen rapidly once the round was blasted and mucked as it is shown on Figure 5b.

At the end of January 2016, a decision was made to change the orientation of the 132-02 drive to intersect the schistosity at an angle rather than running parallel to it. This was an effort to reduce or at least slow down the drive's convergence. A development angle of 45° was proposed to ensure significant results, but for technical reasons, a 20° angle was used. Furthermore, this angle proved insufficient, and the drive's performance did not improve. In April 2016, the orientation was changed again to the 45° angle at some places.



(a) (b)

Figure 5 (a) Early sign of convergence on 132-02 east–west drive 2015-11-12; (b) Rapid convergence on 132-03 sublevel 2016-03-24 support not installed in time

Another geological feature identified early in the area that raised geotechnical concerns was the presence of alternating ground. The contact between the geological 4.3 unit and the geological 4.4 unit (Unit 5) forms a set of interlacing fingers (interdigitation). This type of structure had been identified as 'potentially problematic' in 2015–2016. These fingers also tend to be associated with most of the orebody in the area. However, the level of hazard related to this particular area of alternating ground was not thoroughly understood when initial development and stopping were conducted.

At the time of developing in this area in 2016, the initial response of the rock mass to production was unexpected. Drilling proved to be very difficult, and some holes had to be redrilled up to four times before they stayed open long enough to be loaded with explosives. The result of the blast was also poor, as a significant portion of the stope froze and was never recovered. After that production blast, small changes were observed in the rock mass as well as in the haulage drift, but nothing major. Production and development continued as planned.

2.7 The 3.7 Westwood bang

A seismic event occurred on 30 October 2020, at 14:28 near level 132-03 TB, which provides access to the Z226 lens in the west sector of the mine. At the time of the event, several mining activities were underway in the area, including the remote mucking of stope 132-04/03 block #40. Additionally, a scissor lift team was working at levels 132-05 and 132-04 to prepare the backfill pipe for the stope being mucked. Development activities were also taking place on nearby levels, with two bolters operating at drawpoints on level 132-05, a mucking team at 132-01 PS#43, and another team loading a face in the 133 ramp.

By 15:35, all workers who had taken refuge were accounted for. The truck operator on the mucking team for 132-04/03 block #40 confirmed that the scoop operator he was working with was behind the rockfall caused by the seismic event. At 16:40, communication was established with the trapped worker, who was rescued at 17:45 on 31 October 2020.

The seismic event registered a 2.8Mw on the Westwood mine seismic system, which corresponds to a 3.7 magnitude event on the Nuttli scale (Government of Canada 2020). The event was felt both on the surface and underground by the personnel at Westwood mine, with underground workers reporting dust and rockfalls in various areas of the mine.

Figure 6 provides a view of the seismicity around Z226 captured by the seismic system on 30 October 2020. The circles represent different seismic events, with larger and warmer-coloured circles indicating events of greater magnitude.

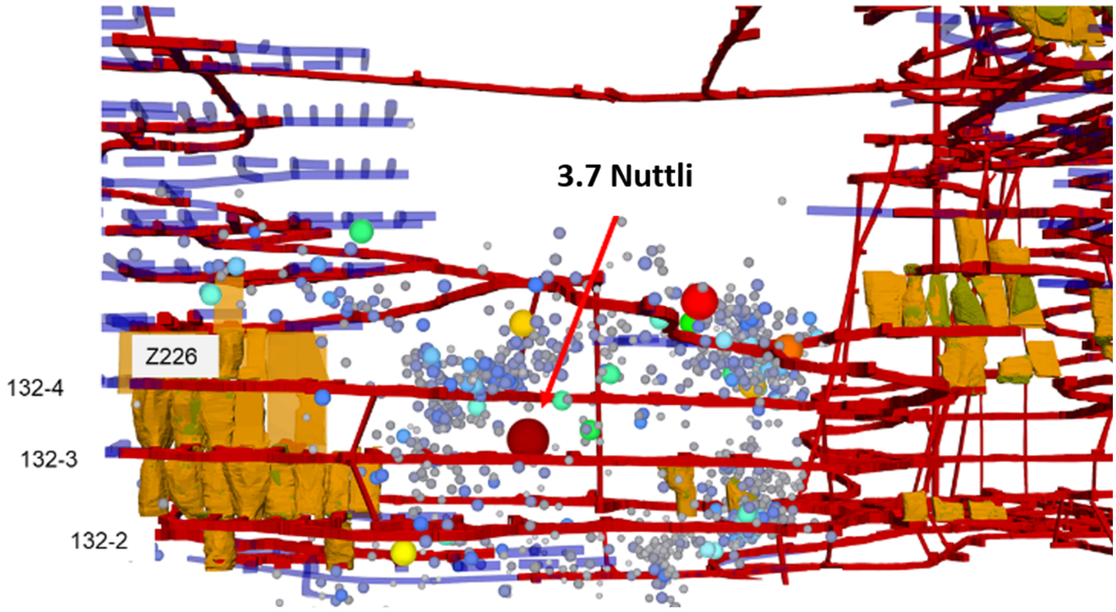


Figure 6 View north of the seismicity on the access levels to z226 during 30 October 2020

2.8 Rockburst damages to underground openings

The known extents of the damages were those observed by the mine rescue teams and the underground workers who were near the area during the event. As of this date, no other employees have returned to levels 132-02, 132-03, 132-04, and 132-05. However, an inspection was conducted on level 132-01. Only minor damages were observed, including a few broken bolts, some small rock pieces fallen to the ground through the screen, cracks, and some loose rock accumulated in the screen. All mine infrastructure outside of the west #3 zone was inspected, and no other significant damage caused by the event was noted. The following four images (Figure 7a–d) summarise the extent of the known and estimated damages at the end of the mine rescue operation on October 31, 2020.

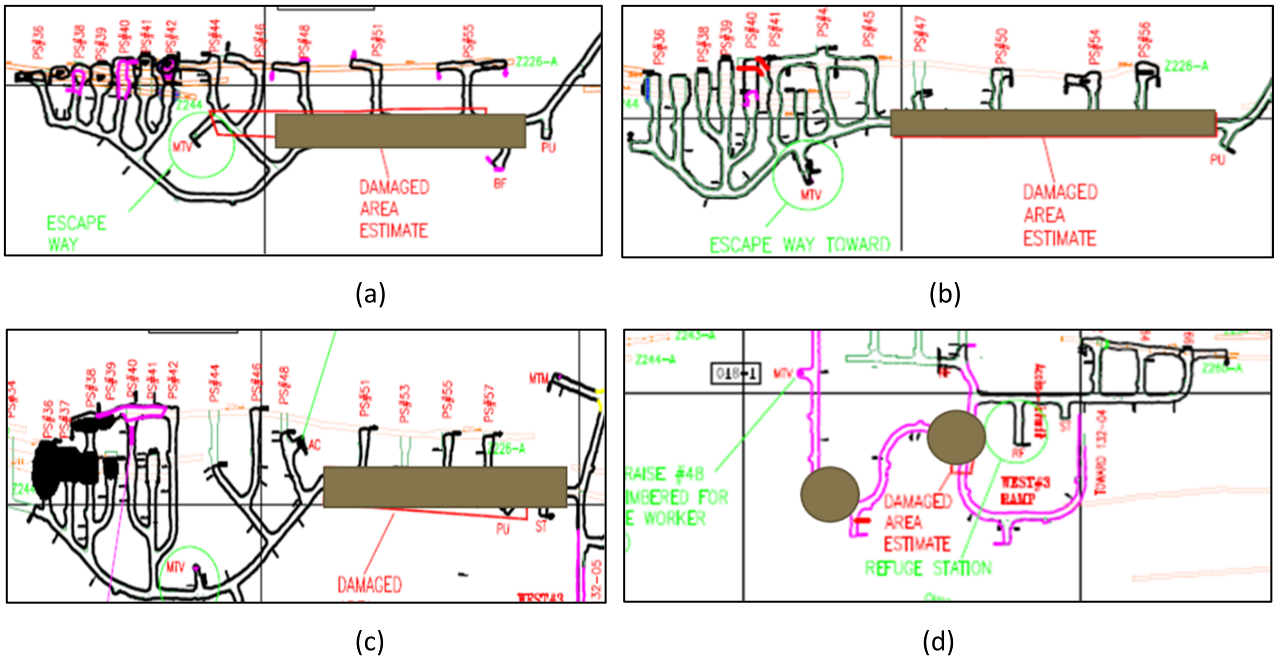


Figure 7 Known/estimated damage extents of October 31, 2020. (a) Level 132-02; (b) Level 132-03; (c) Level 132-03; (d) Level 132-04

The core of the damage zone is primarily located in the 132-02, 132-03, and 132-04 TBW drifts. Figure 8 is a photo taken underground in 132-04 TBW (looking west), illustrating the extent and severity of the damages that occurred.

Figure 8 Example of the underground damage caused by the seismic event on 132-04 TBW (looking west) most of the visible damage came from the wall

2.9 Actions taken following the event

A decision was taken to halt underground development and production to assess the event. On 9 November 2020, a group of technical personal from IMG and consultants were brought to the mine and discussions were held regarding the potential event mechanism, root cause, and path forward. IAMGOLD senior managers took a decision to halt underground operations, it was deemed necessary to take needed time to analyse and better understand the root cause of the event, but also to identify if similar areas of the mine were at risk. A detailed plan of the required work was also put together to utilise mine engineering resources along with internal and external consultants. This officially initiated the formal investigation of the 30 October 2020 event (information taken from an internal memo 2020).

3 The investigation methodologies

The challenges at Westwood mine are highly complex, with limitations affecting every aspect of data input used for engineering design. A primary challenge is the geological and structural uncertainties, which present significant obstacles. Even minor changes or unexpected conditions in the ground, compared to what was anticipated, can greatly impact the performance of local excavations. These uncertainties significantly affect various types of analyses moving forward. A rigorous application of the risk management approach with multiple controls is essential. Given that each mitigation measure has its limitations, addressing seismic hazards requires a multi-faceted approach, relying on various methods and tools, as illustrated in Figure 9.

The Section 4 investigation results will focus on the similarities between the 30 October event and previous significant events at Westwood. Subsequent sections will outline the tools and controls planned to mitigate seismic hazards (taken from an internal company report 2020).

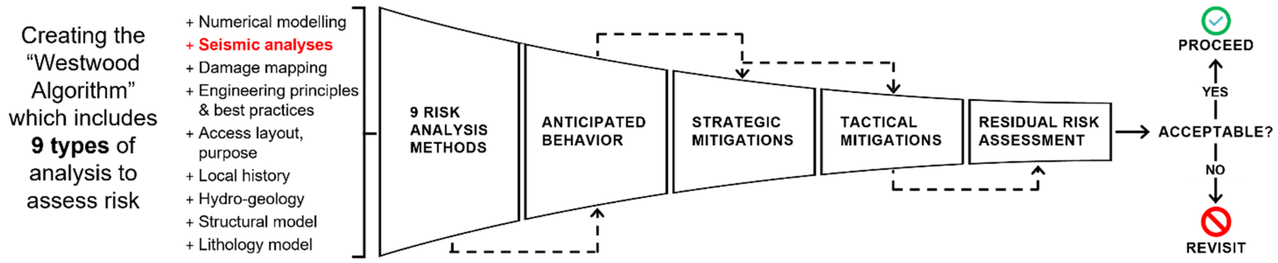


Figure 9 General approach to risk management using multiple controls

4 Investigation results and discussions

The geotechnical investigation following the event was composed of the following axes:

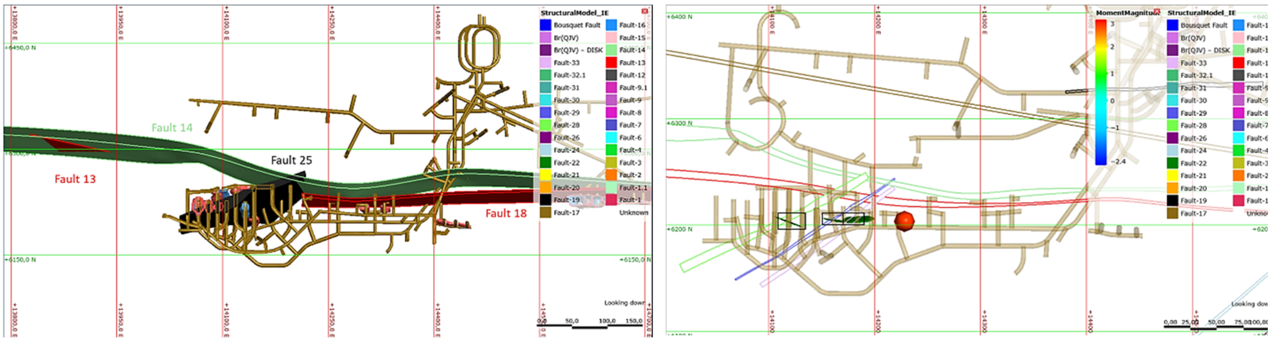
- in-depth thorough analysis to understand the historical decisions that were taken while designing this zone
- updating the geological/geotechnical model
- damage mapping for all underground openings
- in-depth seismic analysis
- multiple stress modelling iterations to yield the correct mechanism and magnitude the seismic event, and the life of mine sequence
- build complex Hazmap model.

Only the following analysis will be discussed in this paper.

4.1 Geotechnical model for (Z226)

Following the seismic event on 30 October 2020, additional work was undertaken to refine the model's accuracy. Structural mapping was conducted on levels 132-01, 132-02 (outside the cave area), 132-05, 132-06, 132-07, and 132-08. An additional investigation was prompted by a drillcore photo near the significant MN3.7 event, which revealed a tectonic breccia. This interval had not been included in any structural interpretations and was not logged as breccia. Due to its proximity to the event, further examination was conducted in the area to locate, identify, and describe any nearby breccias.

These efforts led to several updates in the structural model since the October 2020 event. The changes include modifications of different faults, and the addition of a north–south trend fault. Figure 10 shown the structural model interpretation on level 132-02 to 132-04 prior and post 30 October 2020 seismic event (taken from an internal report 2020).



(a) (b)

Figure 10 General approach to risk management using multiple controls structural model interpretation on level 132-02 to 132-04. (a) Prior to 30 October 2020 seismic event; (b) After 30 October 2020 seismic event

4.2 Seismic domains versus geological domains

Certain geological domains, where different lithologies meet, are known as seismic domains due to their contrasting mechanical properties that can generate seismic activity. The geomechanical parameter of these units are summarise in Table2.

Table 2 Overview of intact material properties and rock mass classification (geological strength index [GSI])

Unit	Rock mass	Intact rock								
					Upper bound			Parallel to foliations		
	GSI classification	Density (10^3 kg/m^3)	Ei (GPa)	v	Uniaxial compressive strength (UCS) (MPa)	mi	Tensile strength	UCS (MPa)	mi	Tensile strength
U3	62 ±2	2.9	81	0.3	154	10	13.3	120	6	21.9
U4	54 ±12	2.83	49	0.2	104	10	10.0	90	7	12.6
U5	52 ±12	2.87	69	0.24	169	13	11.5	135	8	18.5

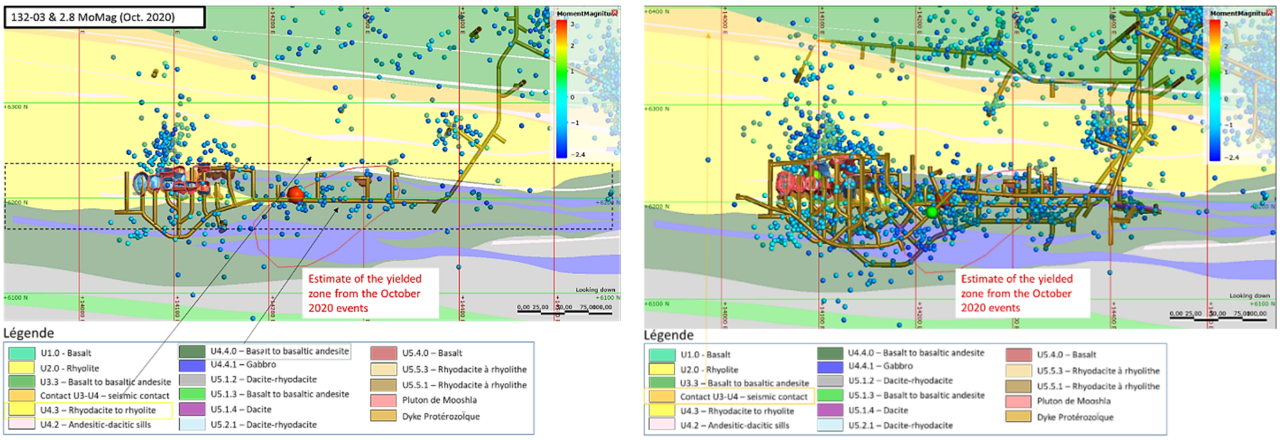
The seismic domains identified in the vicinity of the Z226A lens include: the U3-U4 contact, between units 3.3.0 and 4.3.0; the contact between units 4.3.0 and 4.4.0; and the contact between units 4.4.0 and 4.4.1.

The U3/U4 contact is particularly renowned for its seismic activity and has been associated with significant seismic events in the past, such as those in the 'Relaxed Zone' area of the 104 blocks. Located approximately

100 m north of the October 2020 event, it is not believed to have contributed to the mechanism of that particular event. Figure 11a illustrates the transition zone from 3.3.0 to 4.3.0 (highlighted in orange) in comparison to the seismic events of October 2020 and the affected development.

The boundary between the 4.3.0 and 4.4.0 units is defined by the stark contrast between the soft, felsic, and schistose nature of the 4.3 unit (typically altered with sericite) and the hard, heterogeneous, mafic characteristics of the 4.4 unit, often banded with chlorite and biotite alterations. Development activities across levels 132-1 to 132-09 intersect this seismic domain to some extent.

The east–west drifts severely affected by the October seismic event are situated within the 4.4.0 unit, albeit in close proximity to the contact zone (Figure 11b). When these drifts were constructed between 2015 and 2016, the seismic behaviour related to this contact was not yet fully understood; with comprehension beginning around mid-2018. Generally, based on the team's experience and the broader understanding of seismic activity, this contact is estimated to have seismic implications within a range of approximately 30 m on both sides.



(a) (b)

Figure 11 (a) Seismic U3-U4 contact 100 m north of October 2020 seismic activity (Levels 132-02-0-04, clipping +−30 m); (b) 4.3.0-4.4.0 seismic domain at 132-03 with location of 2.8 moment magnitude (MoMag) event (clipping +−10 m)

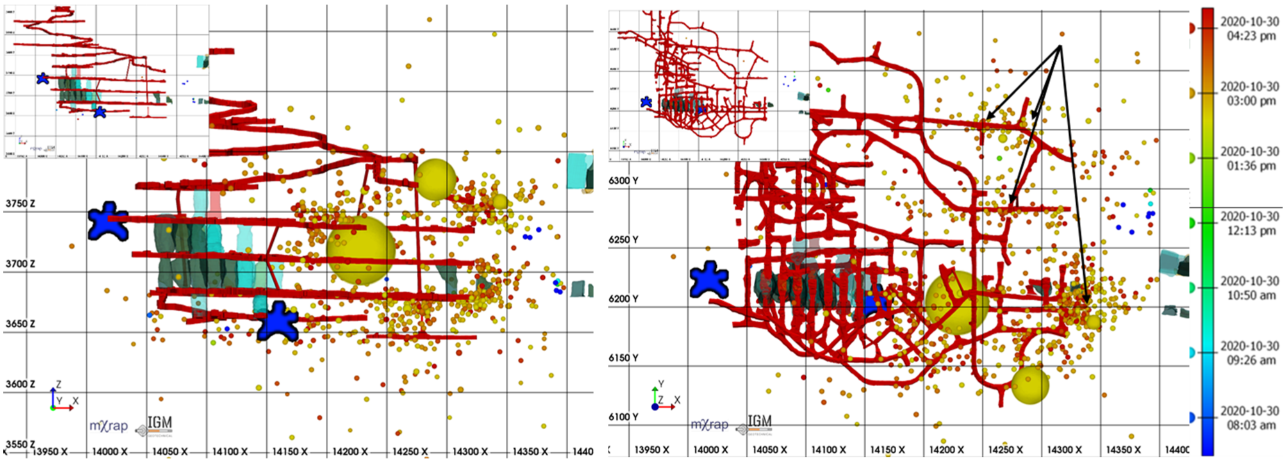
However, the current model resolution does not accurately depict the alternating soft and strong units. Consequently, it is possible that small portions of the 4.3 unit are present within or near these drifts. The prevailing understanding suggests that this seismic contact likely played a role in the October event.

The third seismic domain encompasses all contact areas between the 4.4.0 unit and the 4.4.1 unit, characterised as a gabbro-basalt dyke known for its hardness and brittleness. In Figure 11, these dykes are depicted in purple, illustrating a complex network of continuous and discontinuous formations that exhibit variations in width, appearing to pinch and swell. Particularly near the Bousquet Fault, these dykes display distinct features and can reach widths of several metres.

The affected levels from the seismic event are situated within regions where some of these rigid dykes have been modelled. Current understanding suggests that this seismic domain was another contributing factor to the seismic activity observed in October 2020, among other factors (taken from an internal report 2020).

4.3 Seismic analyses

Based on the spatial distribution of events, two primary populations can be identified. The first population (indicated by the arrows in Figure 12) is closely associated with excavations such as stopes and development drives, exhibiting slight clustering in areas with larger spans like intersections and stopes. These events are likely attributed to secondary strain release resulting from the stress wave impact of the large event on these areas.



(a) (b)

Figure 12 Plot of all events and blasts from 2020-10-30 05:00 to 2020-11-01 05:00. The events are indicated by the spheres and sized according to moment (to indicate relative event size). The blasts are indicated by the star symbols. Both blasts and events are coloured according to date. (a) section view and (b) plan view. The insert at the top left of each plot indicates the events from 05:00 to the time of the large event occurrence.

The second population of events is likely linked to stress and strain changes induced by the large event on the rock mass, including both intact rock and geological structures. During significant events, it is common to observe aftershocks forming linear spatial clusters on related structures. However, this pattern is not evident here, suggesting that the behaviour is more complex than a single large event affecting a geological structure. It is probable that the seismicity source involves the intricate behaviour of multiple structures rather than a singular one.

Figure 13 displays the known geological structures represented by the grey planes, with the prevailing orientations east-southeast and north-northeast. When plotting historical events (ML > 1.5), it becomes apparent that linear structures can be interpreted through the events, aligning with either the east-southeast (orange dashed lines) or north-northeast (red dashed lines) directions, corresponding to known geological structure orientations. Consequently, a spatial plot does not exhibit any predominant structural direction.

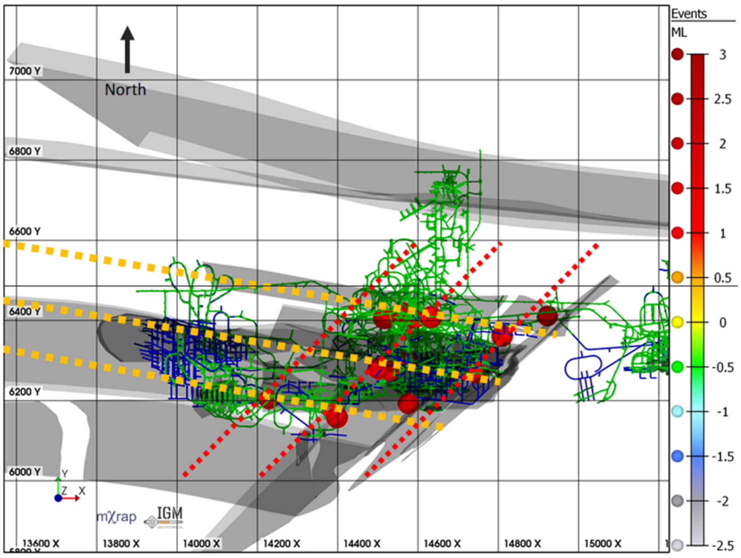


Figure 13 All seismic events ML > 1.5 during the life of mine within 3500-4100 elevation. The events are coloured by magnitude. Development are indicated by the coloured surveys, while the known structures are indicated by the grey surfaces. The orange and red dashed lines indicate linear trends correlating with the predominant structural directions as well as the locations of large seismic events

4.3.1 Trends leading up to the large event

This section examines time trends leading up to the large seismic event to understand the rock mass response preceding the event. Figure 14 displays a magnitude-time chart with a cumulative event count curve (blue line). The black dashed line represents a visual straight line through the cumulative event count curve, highlighting a deviation from the main trend beginning in early September 2020. Due to the strong correlation between underground blasts and seismic activity, the number of blasts is also analysed in the area to determine their impact on the number of events (Figure 15).

Figure 14 shows the cumulative number of blasts for the year preceding the large event, with the overall linear trend indicated by a black dotted line. A visual deviation from this trend appears in mid-September 2020, suggesting an increase in blasting activity in the Z226 area. This increased blasting likely contributed to the higher event rate identified in Figure 15.

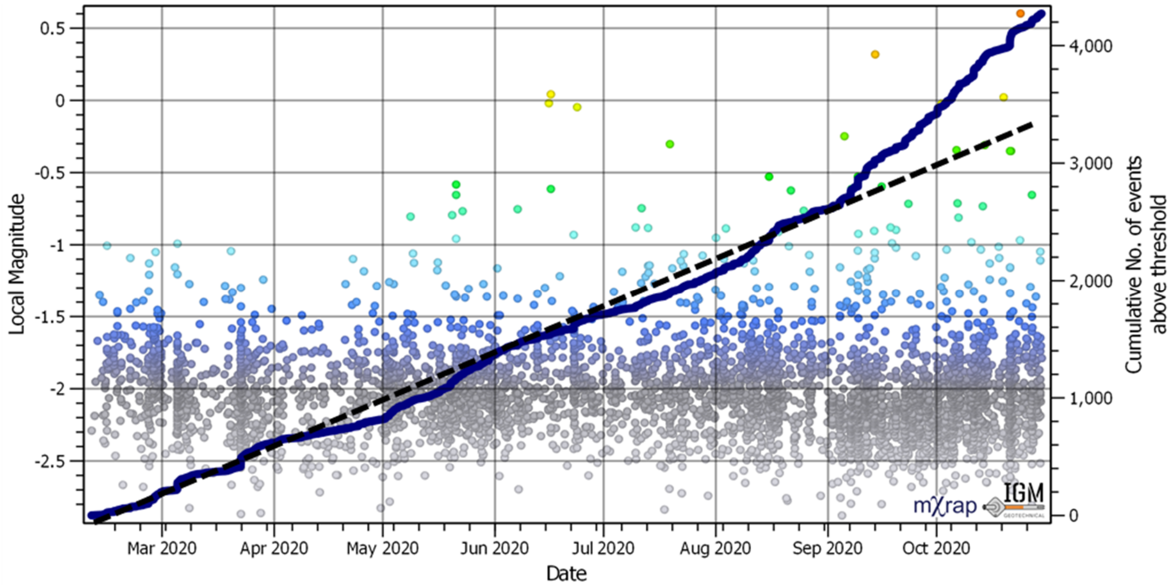


Figure 14 Magnitude-time plot for the Z226 area, with the blue curve indicating the cumulative number of events. The black dotted line indicates the most common linear trend for the cumulative curve

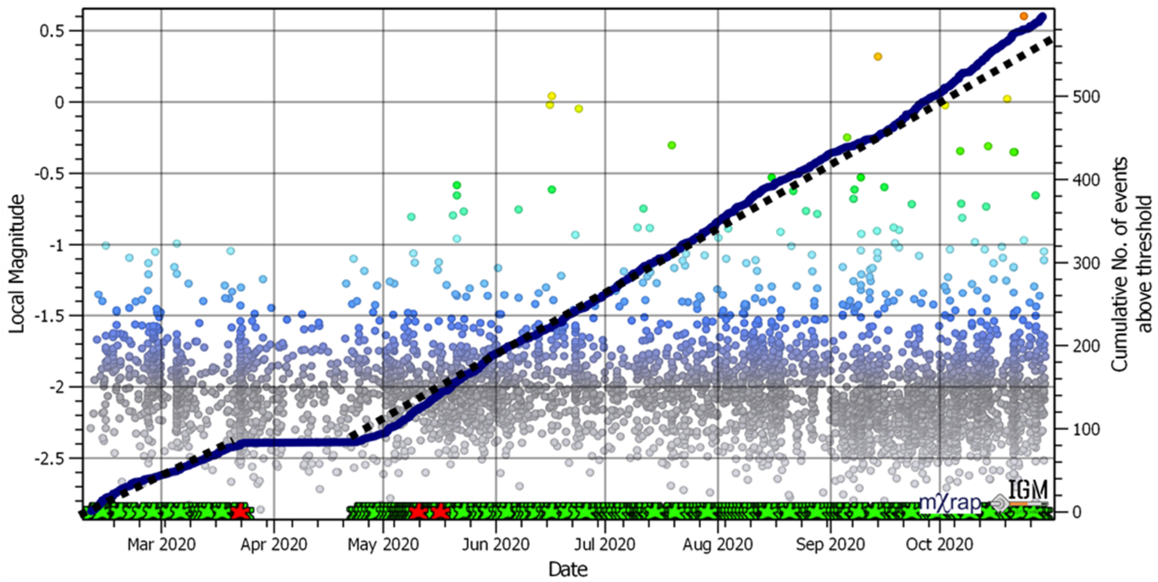


Figure 15 Magnitude-time plot for the Z226 area, with the blue curve indicating the cumulative number of blasts. The black dotted line indicates the most common linear trend for the cumulative curve

Although it cannot be confirmed, the proximity of blasts in time and space likely led to an enhanced rock mass response in the area, especially given that many blasts occurred in moderately to highly stressed rock mass. Most seismic events during this period (from September 2020 onwards) were located near the blast sites, suggesting that they were associated with localised rock mass responses rather than impacting a larger area. However, some events occurred further from the blasts. Although mostly small, these could (in hindsight) indicate unusual behaviour which was not apparent at the time.

The large event (MN3.7) in the Z226 area resulted from a complex rock mass response. This is evident from the event's timing (over nine hours after blasting) and the occurrence of small events throughout the eastern rock mass in the Z226 area. The location of this event aligns with other ML > 1.5 events, but it remains unclear whether these events are associated with predominantly east-southeast-striking structures, north-northeast-striking structures, or a combination of both. This uncertainty makes it challenging to identify which sources could lead to significant large shear events. There were signs of anomalous seismic activity prior to the large event, though these small events were not a concern at the time. This behaviour warrants further investigation to determine if it indicates larger rock mass instability.

The b-value suggests an increased seismic hazard in the area as stopping progressed in the Z226 area, which is typical in stope mining. The seismic hazard rose with an increase in stopping spans, a common occurrence in other parts of the mine. However, this was not a significant concern due to various control measures and designs implemented by the mining team to mitigate this hazard.

A significant increase in events occurred a month before the large event. Initial data analysis shows most of these events were related to localised blasting in a moderately to highly stressed rock mass. However, during this period, events were also recorded in the eastern rock mass. Understanding the blast-event relationship should be a part of investigating the eastern rock mass behaviour, as discussed previously.

The size of this large event exceeded expectations based on the Robson–Whitlock estimation (Robson & Whitlock 1964). Therefore, it is unlikely that an event of such magnitude could be foreseen.

4.4 Stress modelling and investigation conclusions

Several stress modelling iterations were performed (total of 11 iterations), indicating that the area of the recent large event has several 'blocks' formed by faults, contacts, and adjacent levels that have been or are critically stressed. When any of these elements yields, deformation occurs, loads are redistributed and other elements may subsequently yield.

In the case of the large event, extensive damage around the stopes pushed stress levels beyond normal; causing significant yield on the north–south fault. This increased the stress in a section of the inter-level pillar, which eventually failed. When the critical stress in that pillar was reached it yielded, resulting in significant local strain in the adjacent tunnels and further stress redistribution.

This mechanism is similar to other damaging events at Westwood mine, where more extensive than normal stope-induced damage led to greater stress changes and more intense interactions with distant geological structures. For Westwood mine, this means that the most damaging events will not always be closely associated with a preceding stope blast. When an episode of yield occurs, stress and deformation changes can occur across a wide area. Weak or highly stressed spots distant from the initial yield episode could also yield, creating hazards remote from the initial trigger. This was confirmed in the model.

In the west zone, even small mining fronts interact with geological structures and the stress field on a large-scale. The model shows that in the west zone, the volume and magnitude of stress and strain changes induced by mining will increase substantially. Mechanisms of significant instability observed in the model are illustrated in Figure 16 (taken from an internal report 2020).

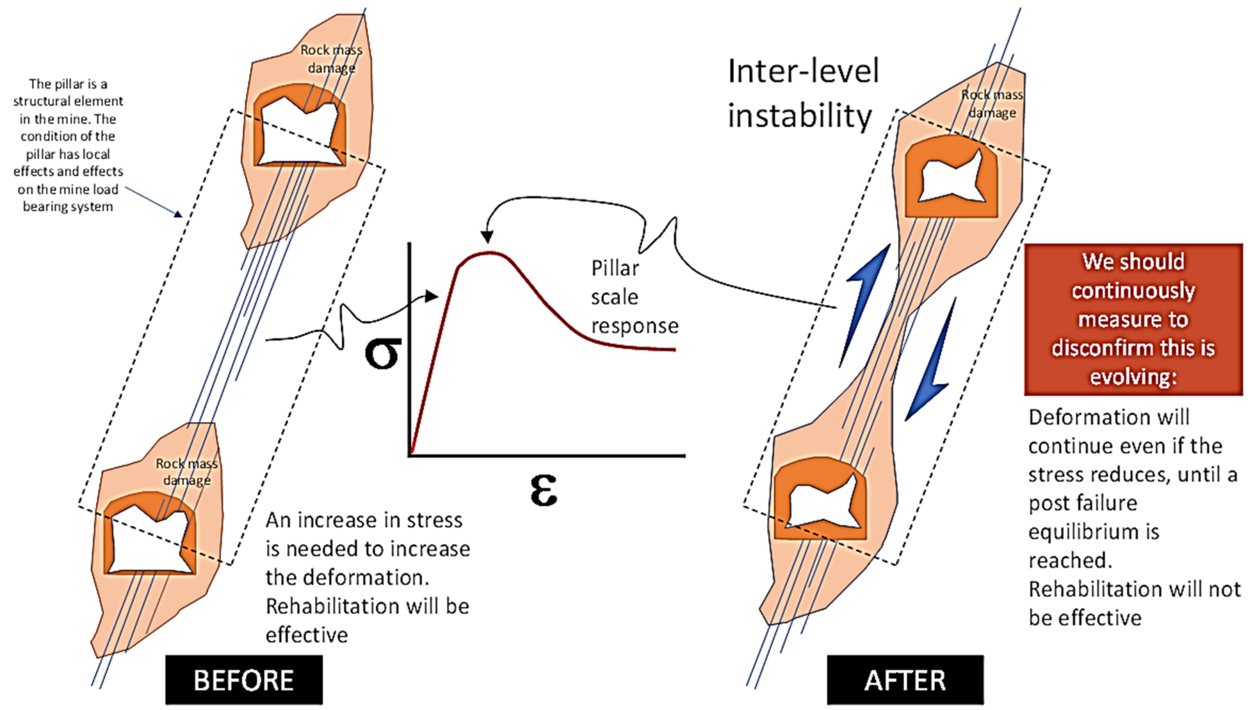


Figure 16 Inter-level instability at Westwood leads to significant stress change and deformation, and therefore high potential for large, damaging events

Figure 17 shows stress in the ramp in 2020 and the locations of large events.

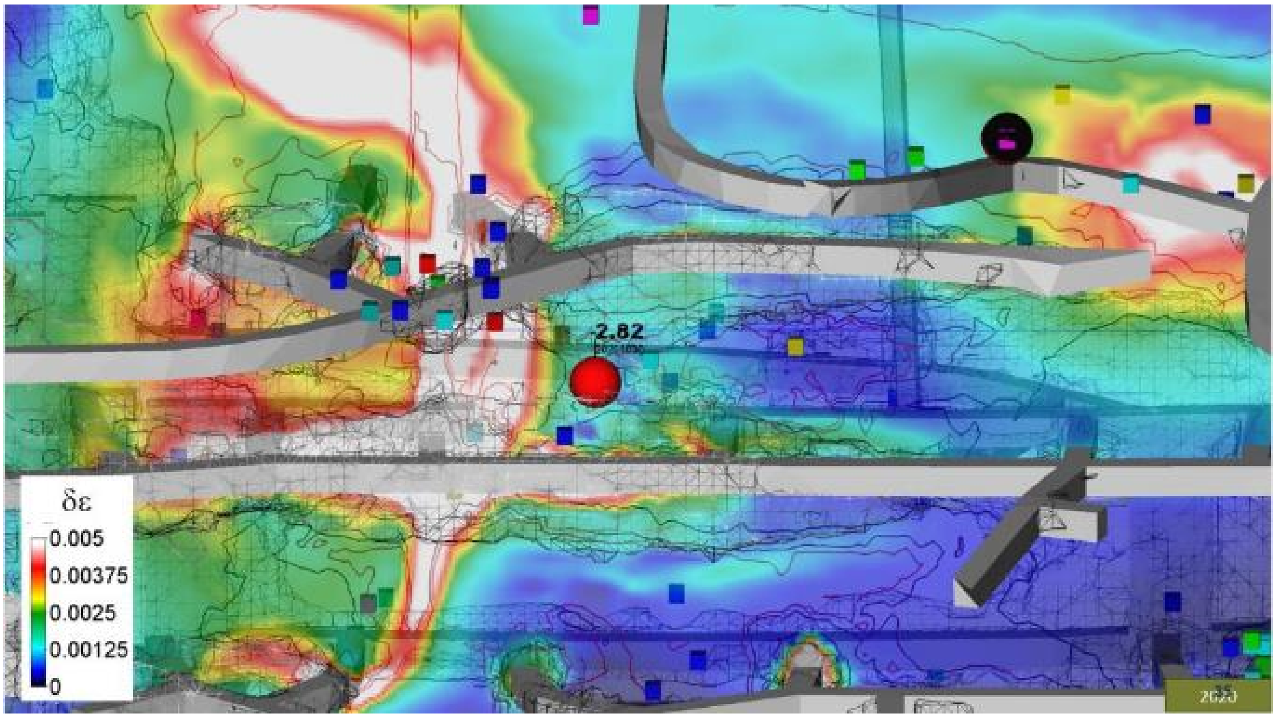


Figure 17 West zone stress, 2020. Shows stress in the ramp in 2020 and the locations of the large events

5 Conclusion

Through this investigation, it was found that the October 2020 event was extremely complex. From this investigation a good understanding was obtained regarding the geology, including the geotechnical domains, their contacts, faulting, fault intersections, and geotechnical properties. Faults were characterised according to their seismic potential, and stress response was simulated using numerical models. Given the complexity of the rock mass response to mining, a robust risk mitigation process that can be fully implemented was necessary, where all decisions are primarily based on ground control considerations to ensure safe mining operations. The mitigation measures implemented to mitigate geotechnical risk at Westwood are detailed in part 2 (*Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic event: part 2 – the mitigation plan*).

Acknowledgement

We would like to extend our gratitude to the management of the Westwood mine for allowing us to publish this study. We also thank the support of all the parties, that contributed to the geotechnical investigation.

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