Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_14

Change in mining sequence and design methods at the Frog's Leg underground mine due to high-stress seismic conditions

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Abstract

Frog's Leg underground mine experienced a change in seismic behaviour in August 2017. The increased stress levels resulted from a combination of increased mining depth, mining span, high-stress bursts of barren pillars, stoping abutment, and shear/slip on seismically active structures.

Extraction sequence changed over years to account for variable orebody geometry, geotechnical constrains, recovery and productivity.

Prior to August 2017, seismic behaviour was predominantly triggered by stope firings and the seismic hazard was successfully managed through exclusion zones and re-entry times. From August 2017, the seismic behaviour changed to random events that were not blast related. Stoping in the Mist was suspended following rockburst damage in October 2018. Due to the increased probability of occurrence and likelihood of exposure owing to the inability of the ground support system to effectively control rockbursts, an alternative method that limited/excluded access to the high stress rockburst-prone areas in ore drives was investigated. As a result, the mining strategy in the Mist changed to side access using footwall drive access with crosscuts into the stress shadowed backfilled stopes.

This paper provides an overview of the measures that were implemented to mitigate the hazard associated with increased mining-induced seismicity and increased stress levels.

Keywords: *seismicity, high stress, footwall drive, extraction sequence, ground support*

1 Introduction

Evolution Mining's Frog's Leg underground mine experienced a change in seismic behaviour in August 2017. This paper provides an overview of how the mine technical services personnel and management addressed the challenges associated with the increase in mining-induced seismicity.

Initially, stoping in the Mist/Fog were mined using the longhole retreat method with island/rib and sill pillars left along strike. Similarly, the upper area of the Rocket was extracted using the same method. Crown pillars were located between these mining blocks. Both mining blocks were partially filled with waste rock and stopes located directly below the sill pillars were backfilled with cemented hydraulic paste fill. Paste fill was introduced to allow full extraction of the orebody.

The central mining area was extracted via a top-down retreat method using longhole bench stoping and backfilled with paste fill. The final 50 m strike length of the diminishing pillar was identified as high risk.

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The mining below was designed as top-down end-access retreat utilising an echelon style stoping front, avoiding the hazards associated with central retreat and diminishing pillars. End-access retreat was implemented to avoid the closure pillars.

1.1 Mine description

Frog's Leg mine is located 600 km east of Perth and 20 km west of Kalgoorlie in Western Australia and is part of the Mungari operation. The mine started as an open pit in 2004, terminated in 2005. An underground operation commenced in 2007 and concluded in 2023.

The ground surface is at 8,340 mRL. Underground workings are accessed through a single decline with the portal located at the bottom of the Frog's Leg open pit. The orebody strikes approximately mine grid north–south.

1.2 Regional and local geology

The Frog's Leg mine is located in the southern portion of the Kundana mining district. The Kundana mining district is a significant mining area in the Archaean Norseman Willuna Belt of the eastern Goldfields Province of the Yilgarn craton. This granite-greenstone belt is 600 km in length and is characterised by a thick, rift-controlled accumulation of ultramafic, mafic, and felsic volcanic, intrusive, and sedimentary rocks metamorphosed through greenschist to amphibolite grades. Successions of greenstone occur in north trending, elongate structural terrains that are bounded by north-northwest trending faults.

Frog's Leg is a structurally complex deposit that occurs within a set of parallel northwest-trending faults associated with the Zuleika shear one (a major regional fault) and along its convergence with the Mungari Shear Zone and various northeast-trending cross-cutting dextral sets, including the Mary Fault (Figure 1).

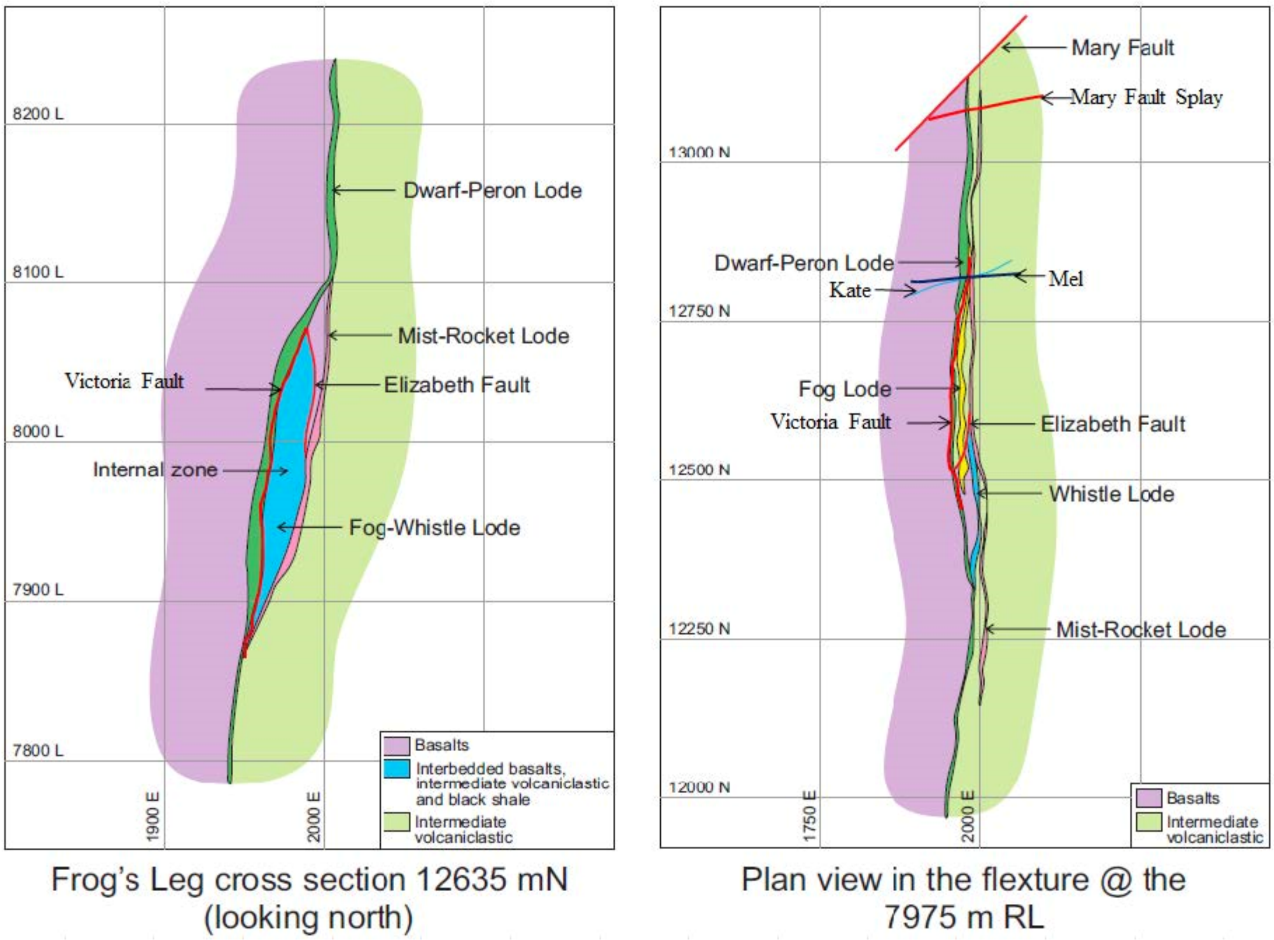

Figure 1 Geological cross-section and plan view through Frog's Leg deposit showing major geological structures and ore lodes

Frog's Leg has two main mineralised zones named the Mist lode to the north and the Rocket lode to the south. Near surface, the Mist and Rocket orebodies are separated by a low-grade zone, although the structure does appear to contribute through this area. Below the 8,050 mRL, the two orebodies link together with economic material extending from the Mist to the Rocket. This zone, where the two orebodies link together, called de dilation zone, is wide (> 30 m), and extends from 8,050 to 7,950 mRL. Below 7,950 mRL, the two ore zones separate once again, where a wide shale unit present in the hanging wall has a negative impact on grade.

1.3 Geological discontinuities

Geological and geotechnical mapping has been conducted to identify the major and minor geological discontinuities that control the failure mechanisms. Microseismic data in conjunction with routine underground mapping were used to validate hazardous structures and identify structures and trends. As can be observed in Figure 1, regional and local geological structures have been identified, and modelled from observations in drillholes and from underground mapping, as follows:

- Victoria Fault, which intersects the Dwarf and Fog lodes and strikes subparallel to the overall ore trend
- Elizabeth Fault, which is also north–south trending, subparallel to the ore lodes and intersects the Mist and Whistle lodes
- Mary Fault, which is located at the northern extent of the Mist orebody and is oblique to the strike of the orebody. However, it is parallel to the maximum horizontal principal stress. The Mary Fault also has numerous parallel splays that can be found at up to 50 m from the main fault and can offset the orebody by up to 14 m to the east. The offset on the main Mary Fault is approximately 400 m dextrally
- there are also several sub-vertical late-stage quartz veins that crosscut east–west to the orebody and persist through multiple levels. These structures are more brittle than the host rock mass and often become seismically active when the mining front approaches.

These discontinuities have the greatest influence on the rock mass response in low and high stress conditions. In low stress conditions, the loss of clamping forces has the potential to create instability as the rock between discontinuities can become free to move and slide due to loss of confinement. In high stress conditions, depending on their orientation in relation to the principal stress, the presence of these discontinuities may cause the structure to suddenly slip releasing energy in the form of a seismic wave. Consequently, these waves are reflected at the excavation boundary, and the resulting stress changes may be sufficient to cause crack propagation, failure, and massive ejection of rock (Villaescusa 2014).

1.4 Geotechnical environment

The Frog's Leg underground mine geotechnical environment is described in the following sections.

1.4.1 Rock mass conditions

The rock mass at Frog's Leg mine is massive with relatively few joints. However, a variable shale unit is present within the contact zone. This shale unit is more predominant in the hanging wall than in the footwall and does not generate seismic activity as it yields very easily at a relatively high loading condition. Mikula (2016) describes the impact of shale on seismicity as follows:

> *'Shales are patchy or variable in spatial extent, and at a small angle to the presumed stress field, resulting in situations where resistance to shearing along shales rests with non-shale bridges. Seismic rupture can then be envisaged.'*

Thus, although shale does not accumulate energy due to early yielding under high stress conditions, this rock type may facilitate dynamic failure nearby.

The ore zone is altered with quartz and carbonate infill in the joints and brecciation with extension fractures. The quartz rich rock, particularly in the ore zone, contains micro-fractures that are susceptible to further fracture under load. Rapid stress changes, especially in the quartz rich ore development, tend to be subject to strain bursting. The intact rock properties are shown in Table 1 and mean Q' values for the rock mass in Table 2.

Table 1 Typical (mean) intact rock properties at the Frog's Leg underground mine

Rock type	Young's modulus (GPa)	Poisson's ratio	Density (kN/m^3)	UCS (MPa)	UTS (MPa)
Basalt (hanging wall)	73.4	0.26	28.9	134	11.0
Shale (hanging wall contact)	–	–	28.5	87	15.0
Ore (altered basalt)	65.7	0.12	28.6	110	18.5
Ore (quartz veins)	–	–	26.2	146	9.0
Volcaniclastic (footwall)	80.3	0.19	27.6	146	24.0
Shale (footwall)	–	–	30.4	166	–

UCS = uniaxial compressive strength; UTS = uniaxial tensile strength.

Table 2 Mean Q' of rock mass domains as Frog's Leg underground mine

Orebody	Hanging wall	Ore	Footwall
Fog/Whistle	38	37	29
Mist/Peron	29	34	27
Dwarf/Rocket	40	38	33

The results of the assessment indicated the following:

- The modified Q-value does not differ significantly across the mining area.
- The data indicates that the footwall is slightly poorer than the hanging wall. This is probably due to the rock defects in this domain having lower joint roughness (Jr), increased number of joint sets (Jn) and slightly lower RQD values.

1.4.2 Stress regime

At Frog's Leg the in situ stress magnitude and orientation were estimated using stress measurements from oriented core, using the Western Australian School of Mines (WASM) acoustic emission technique, described by Villaescusa et al. (2002). The in situ stress measurements for Frog's Leg were undertaken at the Western Australian School of Mines in March 2011 at 414 m below surface and the results presented in Table 3.

Table 3 Summary of in situ stress measurement results

Principal stress	Magnitude (MPa)	Trend (°)	Plunge (°)	Stress gradient (MPa/m)
σ_1	32	222	02	0.0628 × depth + 8.0
σ_2	22	313	11	0.0437 × depth + 4.0
σ_3	13	124	78	0.0340 × depth

The major principal stress is obliquely northeast–southwest to the strike of the Mist and Rocket orebodies and the intermediate stress is oriented obliquely northwest–southeast to the Mist and Rocket orebodies.

The major principal stress is moderate, about 2.3 times larger than the minor stress and about three times the overburden stress.

This stress field gradient appears to be maintained at depth. As such, stress issues and seismicity was experienced at increased depths, especially in the Mist mining area (M7900 to F7725). It should be noted that the initial increase in seismicity was associated with the unfavourable mining geometry of the diminishing pillar above 7,925 mRL. More recent seismic behaviour was high stress rockbursts in the failure zone along the Mist mining abutment.

Although the stress measurement magnitude and direction are considered to agree with those of other mines in the area, increased in situ stress with depth combined with mining-induced stresses was expected.

The results of this were observed at the Frog's Leg mine since the start of 2016, requiring a significant change in ground support design. It was also important that regular life of mine numerical modelling was conducted to ensure that stope geometry, mine sequence and location of primary and secondary access development was appropriate for the stress conditions.

2 Mass response to mining

Prior to 2018, the occurrence of large events and rockbursts ahead of the Mist mining front were strongly associated with stope blasts that triggered the events. Occasionally there were random events (i.e. events not associated with stope blasts); some of these were associated with the Mary Fault and were some distance from active workings or were associated with pillars in areas away from current mining.

This response to mining activity was an important component of managing personnel exposure through use of re-entry windows using the short-term activity tracker (STAT) system. Both geotechnical review boards (GRB) (January 2016 and March 2017) agreed that this was an effective strategy.

Since October 2017 there was a change in the diurnal distribution of large seismic events. Between 2017 and 2018, there were 25 events of ML > 1 or causing damage. The following observations were made:

- Fourteen (56%) were classified as random events; four of these were associated with either the Mary Fault or remote pillars.
- Ten (40%) events of ML > 1 or causing damage were random.
- Six (24%) events resulted in damage and three were due to random events.

The rate of rockbursts between 2017 to 2018 was six events per year; between the 'highly probable' and 'probable' likelihood ratings on the evolution risk matrix. It was possible to convert this rate to a probability of occurrence (Pr) using the following expression (Equation 1):

$$Pr = 1 - \exp(-Rate * T) \quad (1)$$

where:

Rate = the number of events per year.

T = the exposure time in years (e.g. 0.25 for one quarter).

This equates to a probability of 39% in a month, 77.7% per quarter and 99.7% in one year; the possibility of having a random rockburst was about 40% in one year. This does not consider coincidence (i.e. the chance personnel are directly exposed to a rockburst). When coincidence was considered the likelihood (including exposure) was much lower.

This simple empirical analysis indicated that there was a chance of exposing personnel to a rockburst and this increased between 2017 to 2018, hence there was an enhanced requirement for a ground support to protect personnel.

An independent consultant who was involved in the previous GRBs, undertook a detailed review of seismicity at Frog's Leg. This analysis confirmed that random events were occurring and that there was no method to predict these occurrences. The only way to manage this hazard was to limit the amount of damage to the rock mass and identify problematic structures and geometries. These were combined with appropriate ground support.

Several factors contributed to the rockburst, and these are briefly discussed.

2.1 Mining geometry

A ML~1.7 seismic event on 15 October 2017 resulted in significant damage to the F7800 NOD. This event was also triggered by a stope blast, which had also overbroken and reduced the size of an adjacent pillar.

This pillar was directly above the area which experienced rockburst damage on two occasions (13 August 2018 and 3 October 2018). The pillar transferred load onto the area between the 7800 and 7775 ore drives; it was also possible that the pillar may have been the source of the seismic event, but this was difficult to confirm. It was possible that the pillar was at a critical dimension and stress state.

It was noted that mining on the 7825 level had progressed well ahead of mining on the 7800 and 7775 levels and would have resulted in increased stress levels. Mining on the 7775 levels lagged the 7800 level; this meant that there was a standing abutment below and ahead of the F7800N_901 stope. Increased stresses related to the abutment were superimposed on higher stresses in the pillar which resulted in significant damage to the rock mass and deformation in development.

Preliminary numerical modelling undertaken confirmed high stresses in the damage zone. Additional numerical modelling was required to assess improvements in the mining sequence which limits lead/lags and omits pillars.

2.2 Kink zone

There was a prominent kink zone that impacted on the orebody; this area had been associated with increased deformation and rockburst damage on several occasions. It has been postulated that this zone is associated with anomalous localised stress conditions, and this contributed to a poor rock mass response to large seismic events. This was difficult to confirm but anomalous rock mass behaviour at other sites associated with kinks and anticline fold structures have been observed.

2.3 Previous seismicity

There was ongoing seismicity in the area as expected ahead of the mining front. There were also several larger events that were associated with rockbursts on the 7800 and 7775 levels. These would have had an impact on the rock mass and resulted in damage accumulation.

2.4 Seismic damage

Significant damage was observed at F7775 NOD extending about 30 m back from the stope. The damage within about 15 m was catastrophic with the total drive closure and bulking of the rock mass. The broken rock in the drive had the appearance of a blasted muck pile and extended up to the backs. The fragmented nature of this rock and the relatively small block size indicated a high stress environment and that the event was very close to the damage area.

Further back from this area, there was significant drive closure in the order of 2 m. The dynamic cable bolts appeared to have yielded beyond their capacity (300 mm) and the fibrecrete (up to 150 mm in thickness) had cracked. In areas where it was possible to observe behind the fibrecrete the failure zone appeared to be ~1.5 m deep.

In other areas, there was localised spalling and blowouts of the fibrecrete and deformation of bolts. There was also floor heave in areas and overall, there seems to be more stress related deformation than was normally observed.

Typically, there was significant deformation of the eastern shoulder; however, in this area there was also deformation the western shoulder indicating a local change in stress orientation.

Overall, the observations support that the damage was caused by a seismic event that was close by, and it is possible (likely) that the damage zone was within the seismic event source area.

The rockburst damage experienced from a ML1.7 seismic event was estimated to be in the same location as previous seismic damage, with fibrecrete cracking and deformation extending further to the south down the oredrive (Figures 2 and 3).

Figure 2 Rehabilitated area following a seismic event occurred on 13 August 2018, at F7775NOD

Figure 3 Seismic event occurred on 3 October 2018, at F7775NOD. Failure depth estimated at 1.5 m

The small fragmentation size of the failed rock mass was consistent with a burst type event, resulting in fine fragmentation and explosive ejection of the fracture zone surrounding the drive (Figure 4). The initial rockburst damage was observed to have possibly come from the sidewalls, with approximately 1.4 m ejection depth on the eastern wall and ~0.5 m from the western wall (Figure 5 and 6).

Figure 4 Fall of material from the backs, south of the paste barricade. Note how fractured the material is

Figure 5 Seismic event occurred on 3 October 2018, at F7775NOD showing floor heave

Figure 6 Seismic event occurred on 3 October 2018, at F7775NOD, showing loaded cable and Garford bolts

The drive backs appear to have been a secondary failure, following the sidewall ejection based on the location of the ventilation duct in the pile of failed rock. It is also speculative if the extensive failure observed from the backs was shakedown of highly fractured rock triggered by the event after the ejection of the sidewalls, or ejected after the sidewall failure.

The seismic event occurred during a stope firing and therefore was not initially identified during processing. Reprocessing was completed using the triaxial sensor and appears to have resulted in low confidence in location and source parameters.

The estimated event location places it to the east of the orebody about 24 m away. However, when considering the location error (14 m) and source radius for the event, it is likely that the event is very close to the damaged area.

Based on a preliminary visual inspection of the spatial seismic data, two seismic structures were identified that have an east–west trend, perpendicular to the ore zone, coinciding with the inflection observed over several levels in the ore lode.

The most likely nodal plane solution was the one that was in the direction of the major principal stress.

The dynamic ground support system in the sidewalls performed according to expectations in areas where the fibrecrete and mesh was displaced uniformly, with little differential displacement causing shear failure of the surface support (Figure 7).

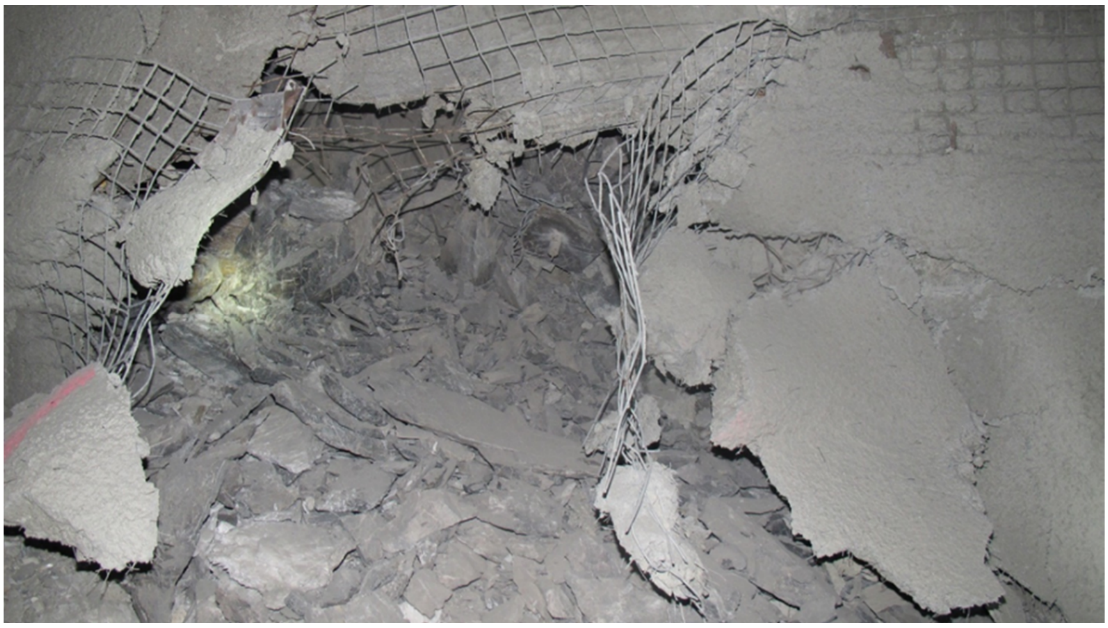

Figure 7 Seismic event occurred on 3 October 2018, at F7775NOD, showing cable bolt with surface support failed around it

The failure observed from the back of the drive was unexpected and was a major concern with regards to ground support requirements going forward. The fragmentation size of the failed rock mass material indicated an extensive fracture zone in the backs of the drive. It was estimated, based on the volume of material observed originating from backs, that the depth of failure was approximately 3–6 m. A 6 m dynamic cable bolt was observed to have been stripped of its plate and was hanging from the backs, indicating yield capacity and/or failure of the barrel and wedge (Figure 8). This allowed the fibrecrete and mesh to fail, losing confinement of the highly fractured rock mass.

Figure 8 Seismic event occurred on 3 October 2018, at F7775NOD, showing Garford bolt yielded to the limit of its capacity

3 Management of changing in mining methods

Several changes have been made since early 2016 at Frog's Leg underground mine.

3.1 Mining methods

The most recent mining method applied at Frog's Leg was longhole open stoping (LHOS) with cemented hydraulic paste backfill. However, due to the occurrence of large seismic events the extraction methodology and sequence was changed.

A sharp increase in damaging events at the end of 2015 and start of 2016 was related to a central retreat diminishing pillar on the M7900 to M7950 levels (Figure 9). Multiple damaging events and falls of ground in late 2015 led to appointment of a GRB in 2016 to review of the mining method and ground support requirements.

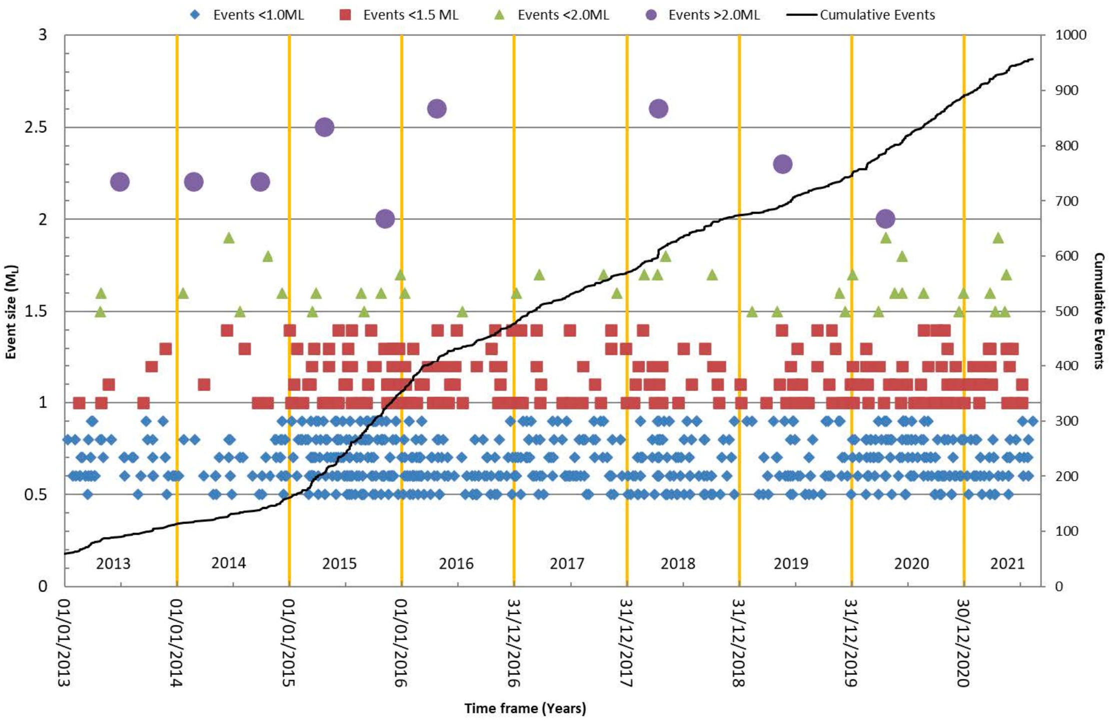

Figure 9 Overview of seismicity at Frog's Leg underground mine from 2013 to 2020

The GRB recommended an end-on retreat method from north to south and mining echelon at 40°. Furthermore, there was a change from a predominantly static ground support system to one with more dynamic energy absorption capacity.

In 2018, multiple damaging events and falls of ground caused a review of mining methods. Rockburst events in late 2017 confirmed the need to increase dynamic capacity of the ground support below the grade line. Due to the high probability of equipment damage to the reinforcement, 4 m cable bolts were installed according to priority.

A change in mining strategy was required due to a catastrophic failure in M7775 oredrive in October 2018.

Factors affecting the occurrence of large seismic events at Frog's Leg mine are considered to include:

- high pre-mining stresses, consistent with other mines in the local area
- increased depth of mining and associated increase in pre-mining stresses
- adverse mining geometry and sequence, and in some locations, the formation of diminishing pillars
- the presence of faults and other persistent structures, and their interactions with the stress redistribution effects associated with mining.

The Frog's Leg mining method started as LHOS with rib pillars progressing to top-down with central access retreat sequence. The inter-level spacing were designed at 20 m with the stope extraction leaving small island, rib and sill pillars to control rock mass deformation and dilution. There were two main sill pillars located at the 8200 and 8120 levels in the Mist orebody and the 8160 and 8100 levels in the Rocket orebody.

These stopes were left unfilled after extraction, although occasional campaign waste filling using uncemented rockfill was conducted in selected areas.

Cemented hydraulic paste fill was introduced at the 8075 level in the Mist orebody, and at the 8025 level in the Rocket orebody, to eliminate the need for leaving permanent ore pillars and to provide local and regional stability of the mined voids. The inter-level spacing was also changed to 25 m but continued with a top-down central access retreat. The unexpected seismic response in the final 50 m strike length of the diminishing pillar (350 m below surface) was identified as a high risk. A formally agreed strategy and risk assessment to minimise personnel exposure was successfully implemented for the final level access.

An end-on retreat sequence was implemented below the 7950 level using an echelon style stoping front, removing the hazards associated with diminishing pillars. At the dilation zone, where the orebody changes in dimension to > 20 m wide, two new technical and operational challenges emerged in the mine plan. First, the top-down extraction sequence relied heavily on the stability of horizontal paste fill exposures and an increased strength was required. Consequently, the cement content or the curing time had to be increased, both with implications in terms of the operating costs and production schedule. The other challenge was mining the wide southern Mist stopes delayed the sequence retreating from south to north as their turnaround time was considerably longer, thus, the northern stoping front moved faster than the southern stoping front.

Therefore, triple lift stopes were introduced in the dilation zone to solve these two challenges. The shape of the stope crown was modified to minimise the horizontal paste exposure and to allow the paste to achieve a natural arch once it was exposed. Although the delayed sequence of stoping fronts retreating south was not resolved, this strategy increased productivity while reducing the paste fill horizontal exposure.

Prior to August 2017, seismic behaviour was predominantly triggered by stope firings and the seismic hazard was successfully managed through exclusion zones and re-entry times. From August 2017 the seismic behaviour changed to more frequent random events that were not related to blast. Rockburst damage during this time affected production due to frequent rehabilitation. The mining echelon was sequence constrained and had no flexibility to mine the above and below levels when rehabilitation was in progress.

Stoping in the Mist was suspended following rockburst damage to the F7775 NOD on 3 October 2018. Due to the increased probability of occurrence and likelihood of exposure owing to the inability of the ground support system to effectively control rockbursts, an alternative method of accessing the orebody that limited/excluded access to the high stress rockburst prone areas in ore drives was investigated. Thorough investigations and analyses were conducted to eliminate exposure to hazardous areas. As a result, the mining strategy in the Mist was changed to side access using footwall drive (FWD) access with crosscuts into the stress shadowed backfilled stopes.

A partial sill pillar strategy was implemented by leaving a pillar at the 7,875 mRL, separating the wide stope areas (7,900 to 7,950 mRL) from the narrow stoping area below the 7,900 mRL. A comprehensive investigation and hazard analyses was conducted, including numerical modelling comparisons.

The general mining strategy with regards to extraction sequence, mining direction and end-on retreat is depicted in Figure 10.

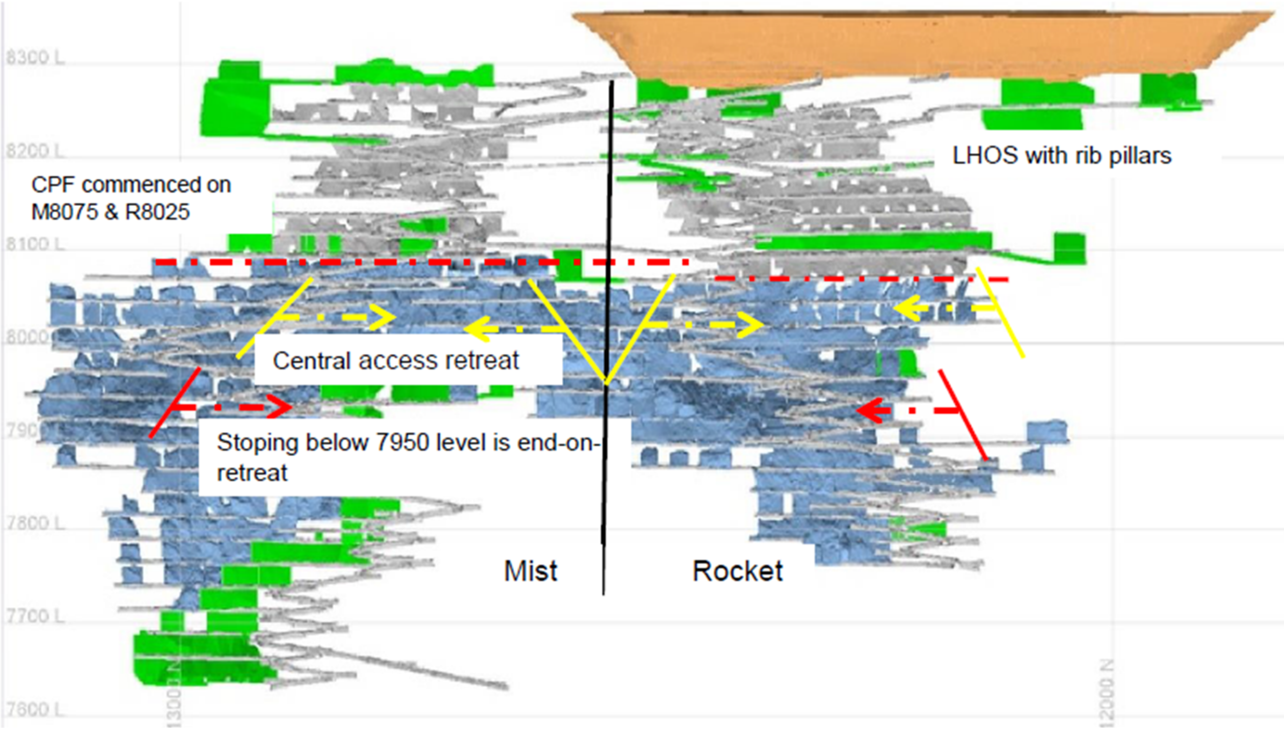

Figure 10 Long section looking east showing the general extraction sequence

3.2 Mist/fog orebody mining strategy

The following strategies were proposed and implemented to re-establish stoping to reduce the seismic hazard to an acceptable level.

The footwall extraction strategy was as follows:

1. Remove all services out of existing Mist ore drives, except vent that will be required.
2. Develop FWD and remote waste into the existing oredrive.
3. If required, use the FWD to drill into and fill existing stopes with paste.
4. Develop crosscut (XC) into paste filled stope.
5. Develop through paste fill to the south.
6. If geometry requires, fire paste rise at south of paste fill.
7. Drill and fire rings from FWD.
8. Bog stope through the XC.
9. Build a fill wall in XC, drill a fill hole, and fill the stope.
10. Repeat from steps 4–10, retreating south.

New rules for the mining method included:

- No personnel access to seismically hazardous areas, such as the abutment in front of stope brows.
- FWDs to be developed a minimum of 15 m from planned stope shapes.
- XCs must be developed in stress shadowed areas (minimum 5 m north of the previous stope brow).

3.3 Ground support design

Based on a seismic hazard assessment the maximum magnitude event associated with the Mary Fault was expected to be between ML2.8 and 3.2, and ML2.1 in the failure zone ahead of the mining abutment. Using an updated ground velocity prediction equation, a peak particle velocity (PPV) of 0.8 m/s was selected, which is equivalent to a ML2.6 at a distance of 10 m from the excavation perimeter.

A site amplification factor of three was adopted to estimate the design ejection velocity of 2.4 m/s.

A static depth of failure of 1.5 m was assumed as the typical fracture zone surrounding the drive. Greater dynamic depths of failure were observed in previous rockburst events close to the abutment and intersections, which exceeded the length of the 2.4 m bolts. The additional 6.5 m long dynamic cable bolts provided a tie back to this primary surface and bolt support, which was expected to act as a reinforced rock bridge integrated by the surface support. Fracture depths were 0.5 to 1.0 m in infrastructure subjected to limited stress changes.

However, following a review, it was recognised that the strong ground motion (SGM) relationship underestimated the incoming ground motion velocity.

The modified Kaiser relationship estimated higher peak ground motion velocities near field, with an increase in difference as the distance from the source increases.

The modified SGM relationship was used to re-calculate the ground support Factor of Safety (FoS) for the various scenarios and is summarised in Table 4.

Table 4 Dynamic ground support design for installed ground support using modified Kaiser ground motion equation 1996 with near field constants (Kaiser 1996)

F7775_GSS: 4 m cable bolts and Kinloks below grade, Garford bolts, mesh to grade, fibrecrete	**Design magnitude**								
Event (ML)		1.7			2.6			3.2	
Distance from source	1	10	50	1	10	50	1	10	50
R0	10	10	10	21.8	21.8	21.8	34.5	34.5	34.5
PPV (m/s)	1.0	0.6	0.2	1.5	1.1	0.5	1.9	1.5	0.8
Mass (kg)	4,200	4,200	4,200	4,200	4,200	4,200	4,200	4,200	4,200
Ejection velocity	3	1.7	0.6	4.4	3.2	1.4	5.7	4.5	2.4
Acceleration (m/s^2)	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Stoping distance (m)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ea (backs) (kJ/m^2)	27.2	14.4	9.0	49.5	29.4	12.4	75.7	51.2	20.1
Ea (wall) (kJ/m^2)	19.0	6.2	0.7	41.2	21.2	4.2	67.5	43.0	11.9
FoS Ea back	1.0	1.9	3.0	0.6	0.9	2.2	0.4	0.5	1.3
FoSE a wall	2.1	6.6	55.9	1.0	1.9	9.8	0.5	0.9	3.4

Using the modifier Kaiser SGM equation and near field constants, the expected design was a peak ground motion velocity for a ML2.6 event 10 m away; which was increased from 0.8 to 1.1 m.s^{-1}. The estimated ejection velocity increased from 2.4 to 3.2 m.s^{-1} , and the design FoS decreased from 1.3 (backs) and 3.3 (sidewalls) to 0.9 (backs) and 1.9 (sidewalls).

Surface support interlinking with the dynamic cable bolt support was considered to be the weak link given the mode of failure observed in the backs of the F7775 NOD.

The sidewalls performed as expected and in most cases the ground support system worked in unison with little differential displacement causing shear failure of the fibrecrete.

4 Progress after change of strategy to closure

The seismic activity rate dropped after 3 October 2018 when stoping in the Mist was suspended. It remained low until footwall development commenced in January 2019 when it increased slightly (Figure 11).

The first stope firing in the Mist was taken on 29 March 2019. The activity rate started to increase gradually to just below the rate before the stoppage in October 2018.

Seventeen large events ML > 1.0 were recorded in the Mist, including an ML2.3 event. Any of these events could potentially have caused rockburst damage in the ore drives. No damage occurred in the footwall access development (Figure 12).

Large events were still being recorded in the failure zone ahead of the mining front, but events are clustered around the ore drives. Ongoing monitoring of the footwall drives have not detected any stress related damage or deformation to date. Seismic behaviour continued as mining progressed in the Mist, but the likelihood of exposure was eliminated.

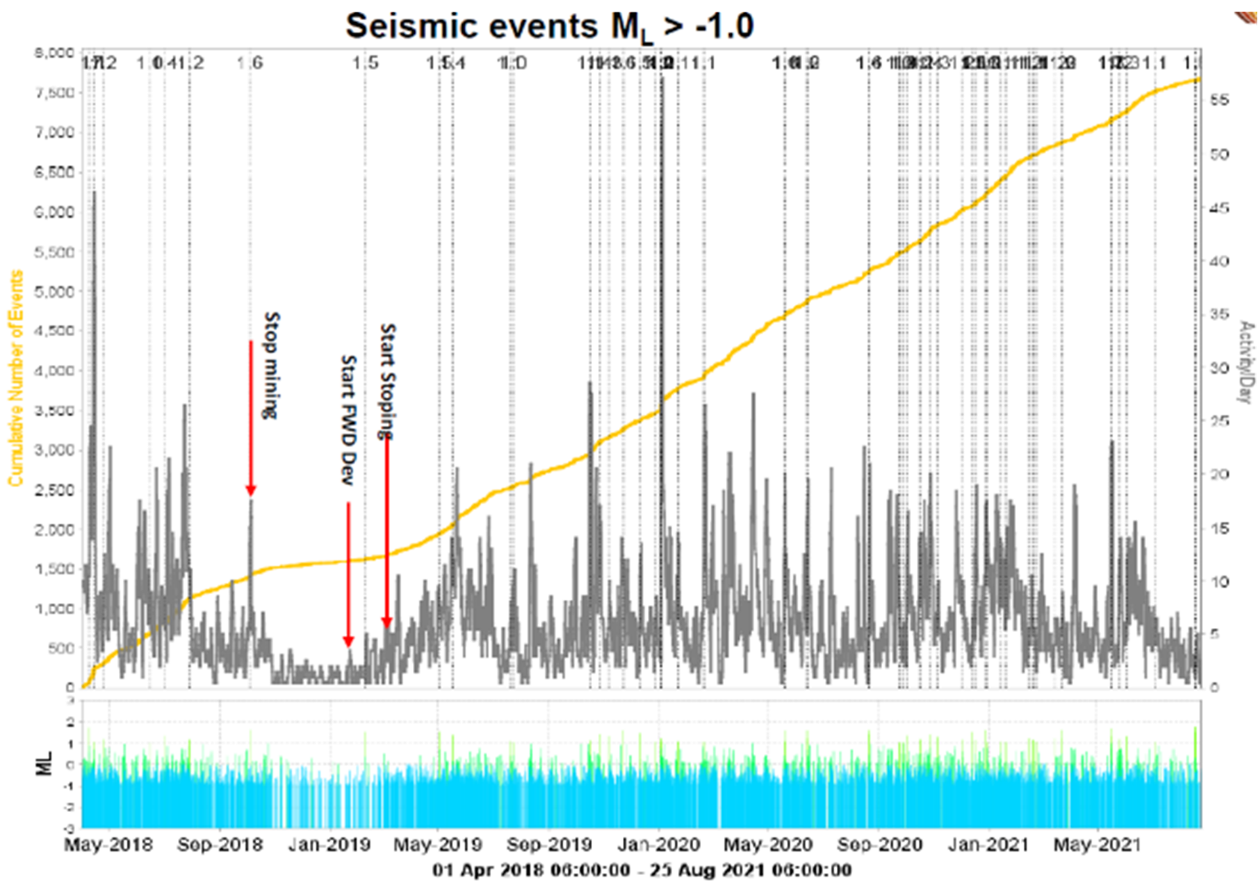

Figure 11 Time history plot showing activity rate in the Mist. The cumulative number of events and events/day shows high activity before the stoppage, a drop during the stoppage period (October 2018 to April 2019, slightly increased when footwall drive development started – January 2019), and significant increase in larger magnitude events when stoping re-commenced (April 2019)

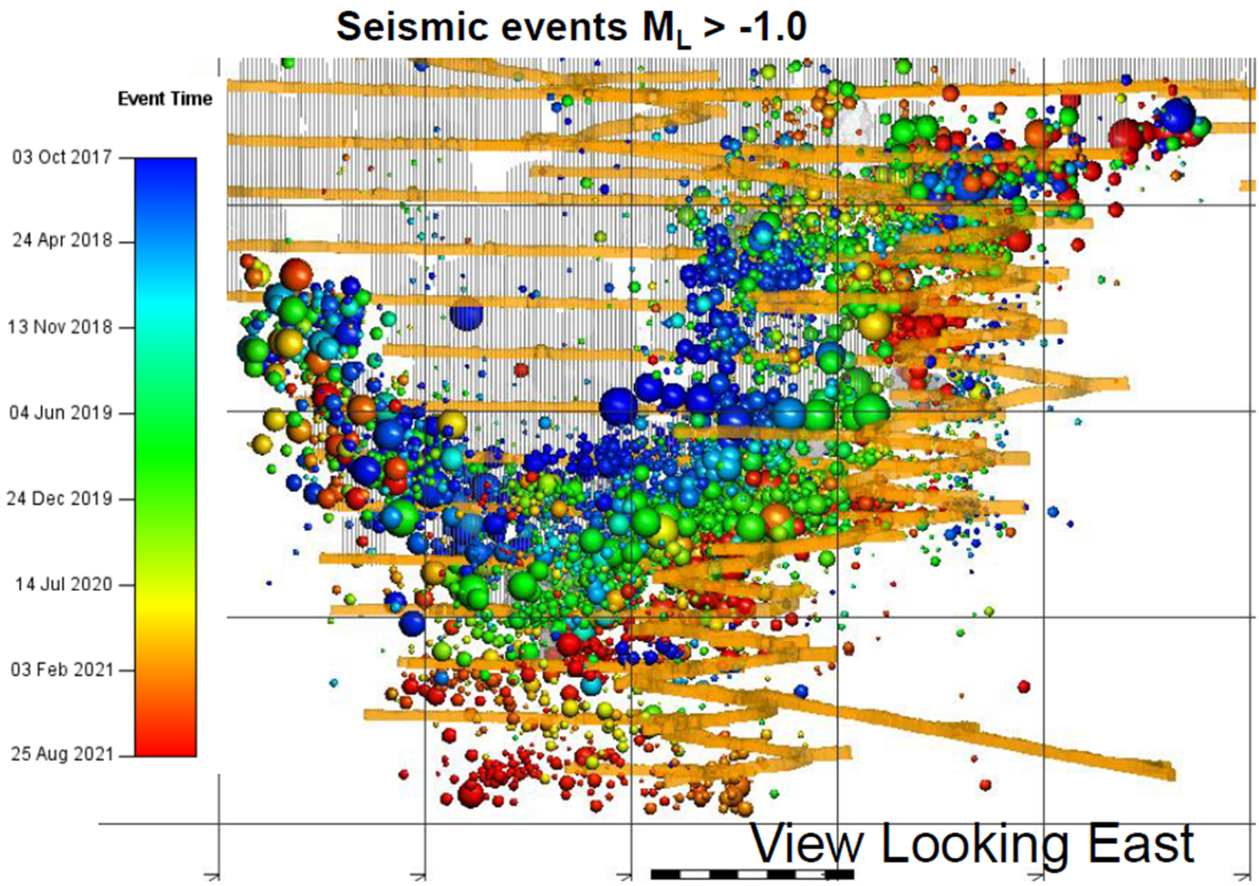

Figure 12 Overview of seismicity at Frog's Leg underground mine from 2017 to 2021

5 Conclusion

The new mining strategy in the Mist eliminated personnel exposure to the seismic risk through re-entry, side access, and ground support. It also eliminated disruption to production with no unplanned delays to conduct rehabilitation to re-establish mining front and associated costs. It reduced the negative impact on workforce morale. Continuation of mining to complete extraction as planned was successful. Without the change of mining method, mining activities would have ceased in 2018 rather than continuing until March 2023.

Large events were recorded in the failure zone ahead of the mining front, but the events were clustered around the ore drives. Ongoing monitoring of the footwall drives did not detect any stress related damage or deformation prior to closure. The same seismic behaviour continued as mining progressed in the Mist, but the likelihood of exposure to the high stress area was eliminated.

Acknowledgement

The authors would like to express extreme appreciation to the management of Evolution's Frog's Leg underground mine for the permission to publish and present the paper and collaboration from the Frog's Leg technical services team. The authors would like to thank AMC Consultants for their support.

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