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Sublevel shrinkage (SLS) mining method: A case study of Newmont's Subika underground (SUG) operations, Ghana

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ABSTRACT

Seismic activity associated with underground mining presents significant challenges to safety, productivity, and operational sustainability within the mining industry. The last three decades have seen increasingly rapid advances in the field of mining-induced seismicity, particularly associated with rockbursts and Fall of Ground (FoG), which have been a major contributor to fatalities in mines. Nevertheless, minimal attention has been devoted to this phenomenon in sub-level shrinkage mining domains. This paper seeks to share the knowledge gained so far by exploring the Newmont Subika underground's sublevel shrinkage mining method and offers valuable insights into the mining industry. The paper seeks to demonstrate the reasons behind the change in mining method from Long Hole Open Stoping (LHOS) to Sublevel Shrinkage (SLS) mining method; pre-work or infrastructure activities conducted in anticipation of the onset of seismicity prior and post change in mining method; underlying mechanisms of seismic events, its current impacts on mining operations, and some mitigation strategies using the three-year seismic data from the Institute of Mine Seismology (IMS) Microseismic monitoring systems at Newmont Subika Underground (SUG) mine, Ghana. Understanding the SLS mining technique and its importance in mitigating seismic-related challenges is crucial for the mining community, given its limited adoption globally.

1 INTRODUCTION

The Newmont Ahafo operation is located along a mineralized zone that extends approximately 70km in the Ahafo Region of Ghana, West Africa, approximately 307 km northwest of Accra. It has been in operation since 2006, with production generated from a number of open pits. Figure 1 shows the Ahafo location relative to Accra and Kumasi. SUG is a down-dip extension of the Subika pit that has been in development since 2012. Underground production commenced in 2018 using a combination of Long Hole Open Stoping (LHOS) and Sublevel Open Stoping (SLOS), with stopes surrounded by permanent rib and sill pillars. Deeper areas are extracted using the Sublevel Shrinkage (SLS) approach, with a sill pillar to divide the two mining methods.

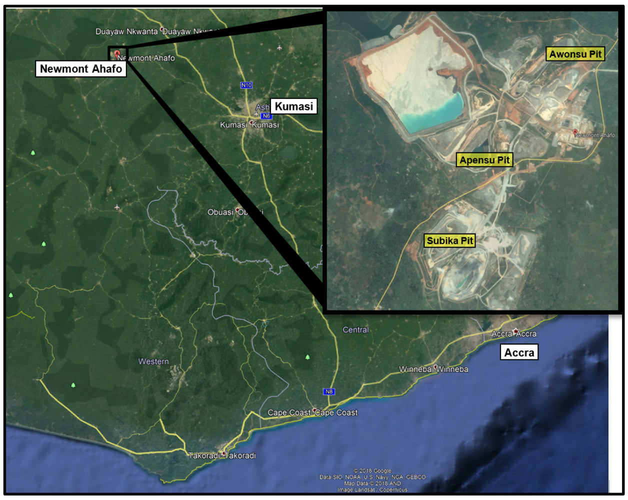

Figure 1 Aerial Photograph of Newmont Ahafo (Google Earth 2018).

2 MINE GEOLOGY

Subika is one of the largest of a group of gold deposits at Ahafo located in the Sefwi Belt as shown in Figure 2. It is developed in the hanging wall of the Kenyase Thrust Fault but lies on a separate and parallel fracture zone to the fracture that hosts the Kenyase-style deposits. The main geologic unit of the Subika underground mine is granitoid. The gold mineralization at Subika is hosted within the Magic Fracture Zone (MFZ), a northeast trending southeast dipping (~045°/65 SE) zone of brittle fracture and veining ranging between 50 to 100 m thickness, with mineralized lenses, which vary in width from 2 to 20 m.

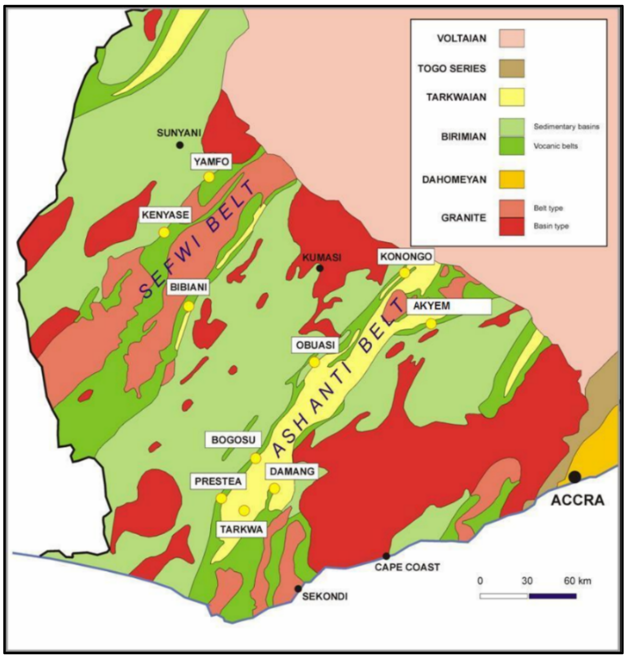

Figure 2 Geology of Southwest Ghana.

Five main structural zones, including the Victor Fault, Kaalbas Fault, Hatch Zone, Deep Fault and Denis Fault, are described, each exhibiting distinct characteristics and orientations within the Subika formation as shown in Figure 3.

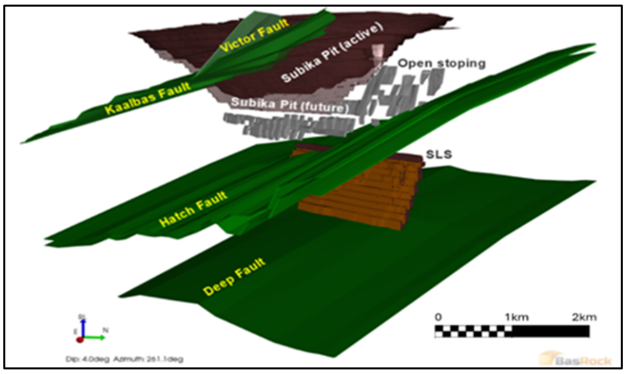

Figure 3 Structural Zones Relative to the Subika Pit and Underground Workings.

2.1 *Rock mass Characteristics*

The Subika deposit is in a sturdy granodiorite formation and lies in the hanging wall of the Kenyase Thrust. The orebody has a steep dip of about 70°, while major faults have a gentle angle of 20° to 30°. These faults are generally capable of causing local instabilities and are managed based on local conditions.

The Uniaxial Compressive Strength (UCS) is estimated at 154 MPa, based on a Weibull model fit using 113 sample test results from 2009 to 2018. Additionally, tests on 281 samples indicated a Young's Modulus of 73 GPa, with Poisson's Ratio set at 0.31, determined from a Weibull fit on the dataset. Stress measurements conducted at Ahafo using Acoustic Emission (AE) and Hollow Inclusion (HI) cell methods at different times revealed the following (GCMP, 2023):

i. Sigma 1 (σ_1) is sub-horizontal, roughly aligned from east to west and approximately three times larger than Sigma 3.

ii. Sigma 2 (σ_2) is similar in magnitude to Sigma 3.

iii. Sigma 3 (σ_3) is sub-vertical and roughly equal to the overburden stress.

3 MINE DESIGN

3.1 *Mining History*

The underground study of the Subika orebody commenced in 2005 with full scale mining operations commencing in January 2006 as an open pit.

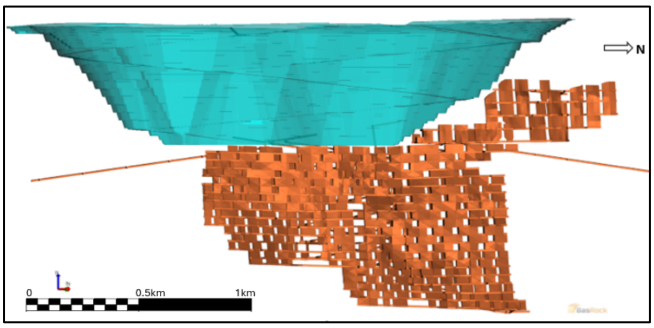

Figure 4 Initial Business Case for the SUG project with Phase 4 pit design.

The SUG project, as shown in Figure 4 above, was intended to become an underground mine to access the gold ore deposit beneath the Subika pit, separated by a crown pillar below the ultimate Phase 4 open pit layback scheduled to be completed in 2025. Underground mining commenced in May 2017, using a combination of Long Hole Open Stoping (LHOS) and Sub-Level Open Stoping (SLOS), with the first production ore in 2018.

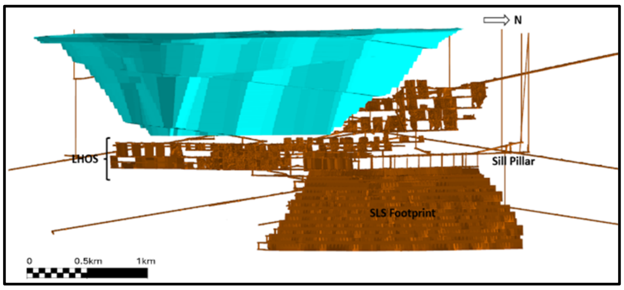

Figure 5 Final Approved business case for the SUG project with Phase 4 pit design.

3.2 Change in Mining Method

In response to geotechnical challenges i.e. the adverse in-situ stress conditions and variations in the rockmass quality experienced in few months into production, a geotechnical review was conducted in April 2018. This revealed the aggressive nature of the initial geotechnical guidance which had permitted high extraction ratios, slender pillars and no consideration for backfilling opened voids. Revision of the assumptions to allow reduced extraction ratios and backfilling of open stopes with waste rock resulted in the original business plan for SUG no longer being viable in terms of using the LHOS and SLOS mining methods at depth. A cross-functional team consisting of Newmont's geotechnical team and external subject matter experts was established to identify an alternative mining method for SUG and address the near-term impacts on the operation. Sublevel Shrinkage (SLS) was selected in 2019 as the preferred mining method as it addressed the challenging geotechnical risk profile and maintained economic value. The new business case layout is shown in Figure 5. In order to ensure seamless mining operations, a 50m thick sill pillar (750 - 700 mRL) was left to separate the upper stoping area (SLOS and LHOS mining blocks) from the proposed SLS mining block.

3.3 The SUG SLS Method

Generally, the SLS mining method utilizes a production front similar to a sublevel cave (SLC), except that unconsolidated fill (waste or low-grade rock) is placed in the caved zone on top of the broken ore to stabilize the surrounding rock mass and prevent the overlying strata from caving uncontrollably as shown in Figure 6 (Mackay et al., 2014).

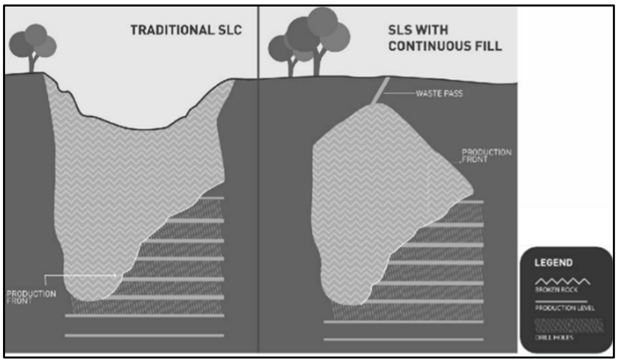

Figure 6 Sublevel Cave (showing caving of overlying strata) versus Sublevel Shrinkage with Continuous Fill (after Mackay et al. 2014).

The SLS at SUG is based on a transverse layout with drawpoints centers spaced at 15 m and sublevels spaced at 25 m. Fifteen (15) vertical fillpasses spaced at a 50 m interval were created in the sill pillar to serve as backfill channels for the SLS void as shown in Figure 7. Caving started below the sill pillar (underside width of 15m) at 680mRL and is planned to progress to 410mRL.

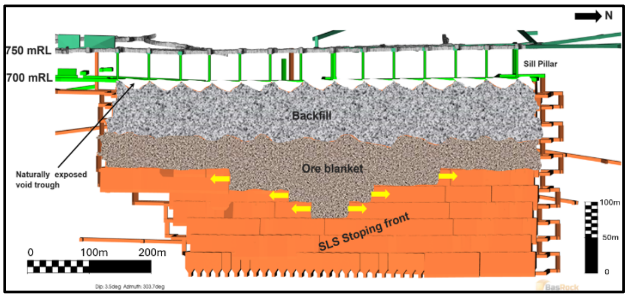

Figure 7 Schematics of the SUG mining method.

The slot drive is developed on the northern side of the orebody-hanging wall contact, with production retreating in a Chevron pattern towards the footwall. The voids created are filled with waste rock sourced from underground development and the Subika open pit. As mining progresses downward, this fill material settles into the gaps and is topped up regularly to support the stope abutments. However, natural troughs shown in Figure 7 above remain exposed and unsupported throughout the Life of Mine (LOM). Figure 8 shows a typical layout for level development at SUG.

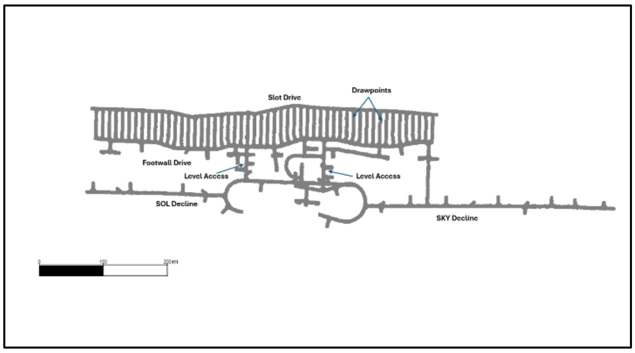

Figure 8 **SUG SLS transverse layout and mining front, 635mRL.**

4 MINE INFRASTRUCTURE IN PREPARATION TOWARDS ANTICIPATED SEISMICITY

Seismicity was not considered a threat to the survival of the Subika mine from the onset of mining activities based on the available geotechnical data from the limited excavations developed at the start. However, after several months of production, the emergence of low frequency rock noise with erratic ejection of rock pieces from active development and stoping ends prompted a re-evaluation of this assumption. Bawden (2011) after extensive evaluation concluded that mine seismicity could be expected once the maximum induced stress exceeds about 0.4xUCS, and that more intense seismicity could be expected when induced stresses exceed 0.6xUCS.

In September 2018, results from the first set of HI-cell tests confirmed the underground principal stress was 30% higher than estimated and oblique to the orebody, placing it in shear. The combination of the two factors suggested SUG would experience mine seismicity at relatively shallower depths. In anticipation of this, seismic monitoring systems, extensometers, rockfill monitoring sensors and stress meters were installed within the underground excavations, with the planned expansion of coverage at deeper parts as mining progresses with the introduction of the SLS mining.

4.1 Seismic System

In general, routine seismic monitoring in mines enables the quantification of exposure to seismicity, providing a logistical tool to guide the effort into prevention, control and prediction or warning of potential rockmass instabilities that could result in rockburst (Jager and Ryder, 1999).

The current microseismic system installed by the Institute of Mine Seismology (IMS) at SUG was commissioned in November 2019 and consists of twelve (12) 14Hz triaxial sensors installed at various locations underground to determine potential seismic clusters in response to mining as shown in Figure 9.

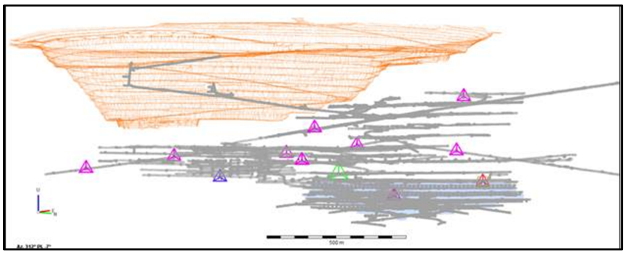

Figure 9 **Seismic sensor locations at SUG (looking East).**

Seismic monitoring at SUG aims to provide event information, assess seismic characteristics and hazards, monitor fault-slip potential during mining, understand rock mass responses to seismic activity, and minimize personnel exposure to such events.

The Microseismic system records seismic events on a relative scale known as “Local Magnitude (M_L)” and provides information about the size or energy release of the seismic event. All seismic data are processed daily, viewed and analyzed using the IMS Ticker3D and Synapse software packages as shown in Figure 10.

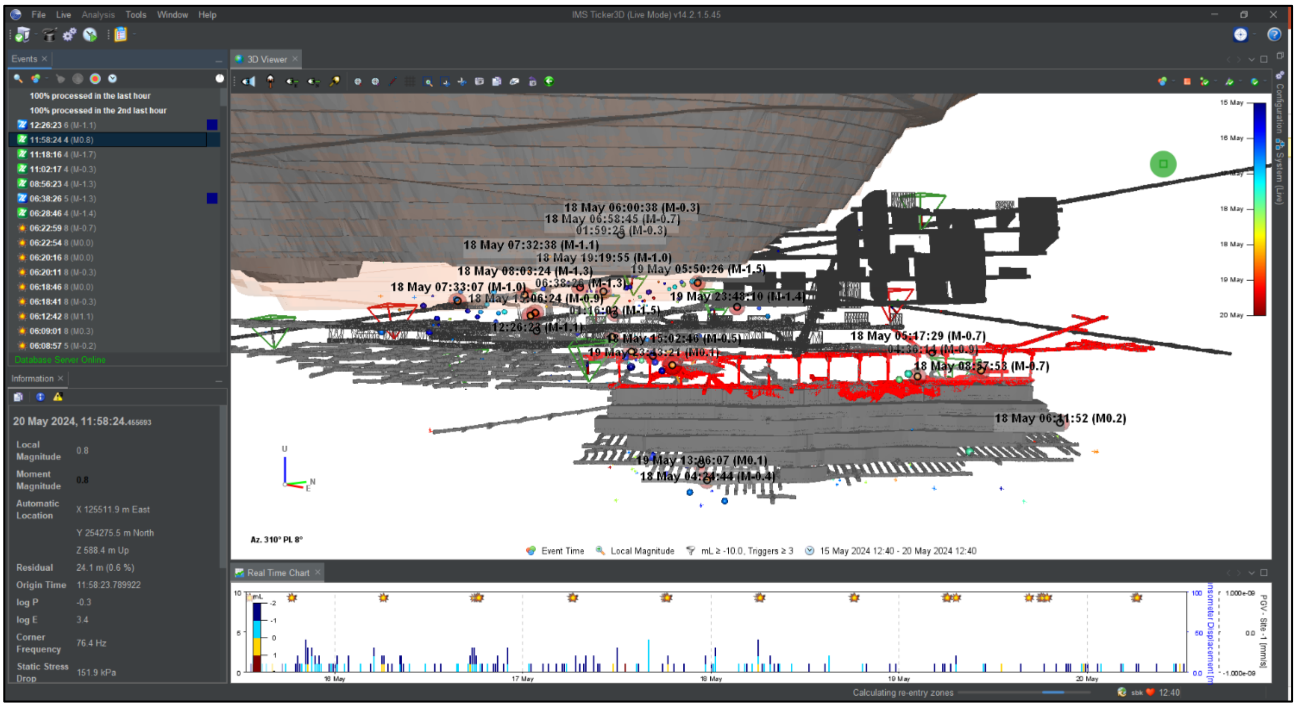

Figure 10 General overview of IMS Ticker3D.

4.2 Ground Deformation/Displacement Device

Deformation measurement instruments, namely Multiple Point Borehole Extensometers (MPBX) and stress meters are installed at selected points along the sill pillar to monitor the rock mass response to mining.

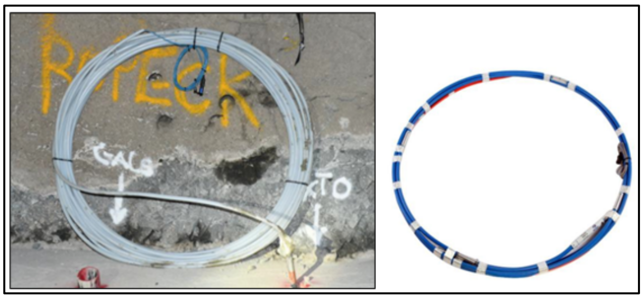

Figure 11 Deep-hole extensometer MPBX installed at Subika Underground.

4.2.1 Multipoint Borehole Extensometer

Six (6) channelled MPBXs with integrated electronic readout heads were installed at 14 locations along the sill pillar to monitor the vertical displacement within the pillar. An MPBX measures the deformations of a section of rock mass by examining the movement of an internal rod relative to an anchor point (or “head”). Movements of the rock mass around the borehole are transferred to the attached anchors and recorded by transducers placed at the top of the borehole. Figure 11 shows an installed MPBX.

4.2.2 Vibrating Wire Stress Meter

As SLS mining advances, stress levels within the sill pillar will change, necessitating the monitoring of pressure changes in rocks through stress meters. These stress meters are installed at a 25 m borehole depth to precisely measure stress variations at the core of the sill pillar. Figure 12 below shows the vibrating wire stress meter.

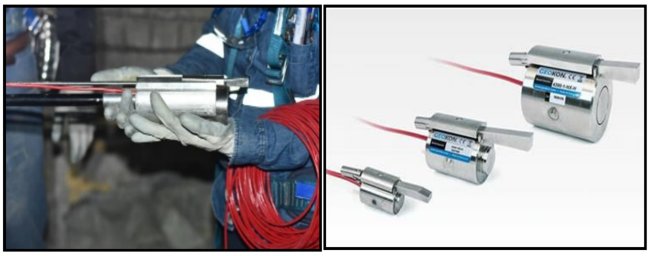

Figure 12 Vibrating wire stress meter.

Figure 13 shows data from the MPBX, and stress meters installed along the sill pillar as analyzed on a weekly basis.

4.3 Rockfill Level Sensors

The Subika underground infrastructure setup for rockfill delivery is situated on the 750 mRL, where 4 m diameter underground fill passes are used to introduce waste material into the SLS void. The necessity for continuous backfill to fill the void formed during ore extraction is emphasized by Mackay *et al.* (2014) as a crucial measure to mitigate the potential risks associated with SLS mining (long-term stability of mine infrastructure and the potential for air blasts).

One of the guardrails for maintaining the integrity of the SLS fill passes is to keep them full to prevent potential ground 'erosion' along the stope walls. To operationally manage this, rockfill level monitoring sensors have been installed to monitor the levels of fill material in the fill passes to avoid 100% downward movements in the fill columns. All components of the rockfill monitoring sensors have been synchronized to give traffic indications about the fill column thresholds as shown in Figures 14 and 15.

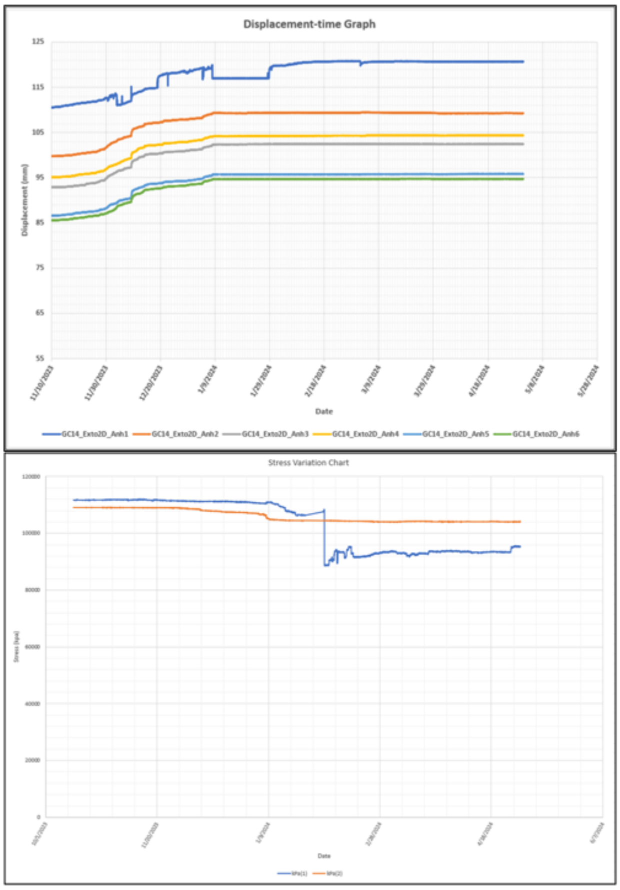

Figure 13 Graph of extensometer and stress meter readings.

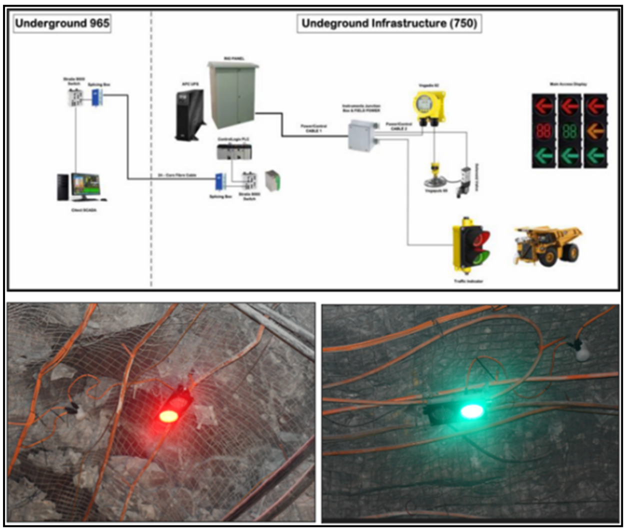

Figure 14 Rockfill monitoring system architecture.

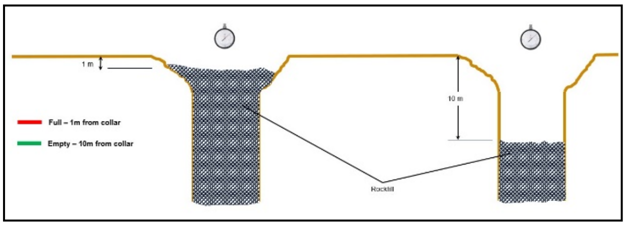

Figure 15 Rockfill monitoring bin level sensor range.

4.4 Cavity/Void Survey

To monitor the health of the SLS void and identify potentially unstable ground conditions, the Subika operation employs the C-ALS (Cavity Auto-scanning Laser System) tool to scan/survey inaccessible voids created from stoping activities. Figures 16 and 17 show processed scan images from the C-ALS scan.

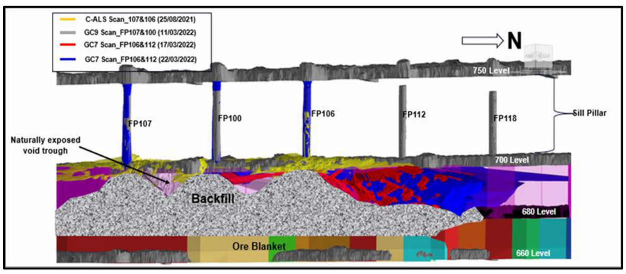

Figure 16 Subika SLS cave and void scan.

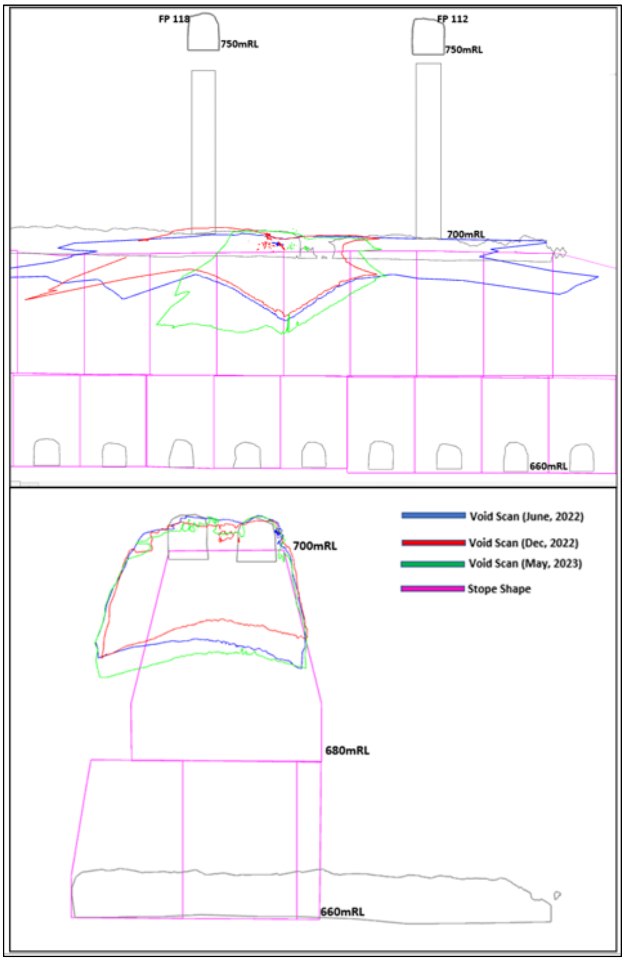

Figure 17 Comparative analysis of void scans.

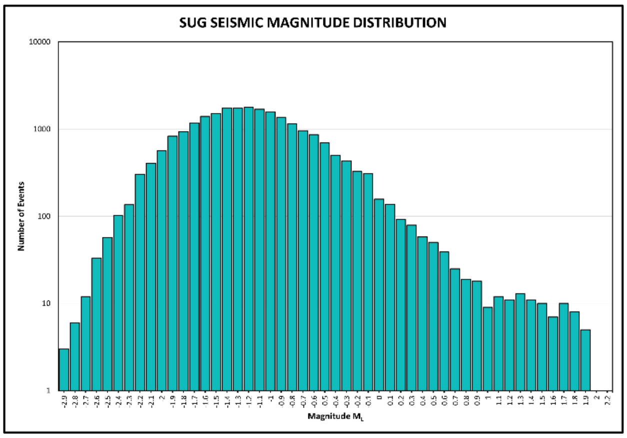

Figure 18 Seismic event magnitude distribution for SUG.

5 UNDERSTANDING SEISMICITY AT SUG

Seismic hazard is an issue at SUG primarily due to the high major principal stress, deviatoric stress field and a high shear component on the orebody.

SUG has experienced a number of damaging seismic events since its transition to SLS mining. Figure 18 shows the all-time seismic event size distribution for SUG.

Table 1 illustrates the annual changes in seismic response, showing a significant increase in both the number and magnitude of large events recorded each year. This trend highlights the urgent need to implement measures to reduce seismic risk exposure underground.

Table 1 Summary of seismic events recorded on a yearly basis

PERIOD	Number of Events	Events with ML>0	Largest Event
Nov 19 - Oct 20	535	19	0.7
Nov 20 - Oct 21	392	20	1.2
Nov 21 - Oct 22	3637	152	1.7
Nov 22 - Oct 23	9983	207	1.9
Nov 23 - Apr 24	6019	218	2.2

Figure 19 is an image of the seismic events trend observed.

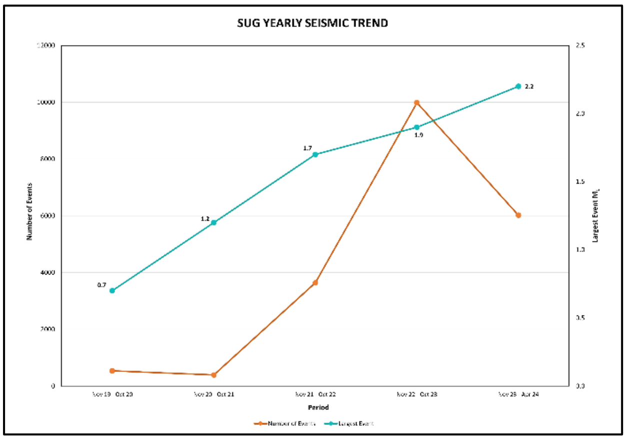

Figure 19 SUG seismic trend.

For a given stress state, a lower rock mass strength implies a greater potential for rock fracturing, rock mass deformation and excavation instability. Seismic hazard at SUG is well defined and understood with elevated seismic risk experienced in the EMPEROR (East) mining block as compared to the YODA (West) mining block.

The EMPEROR mining block has a greater density of discontinuities (faults, joints, dykes) resulting in a weaker rock mass strength. The reduced rock mass strength makes this block more susceptible to stress induced damages (stress induced rock fracturing and FoG) following the occurrence of seismic events. Since the inception of SLS mining, all seismic induced FoG events recorded have occurred in the EMPEROR mining block. Figure 20 shows the location of the abovementioned mining blocks on the 610mRL.

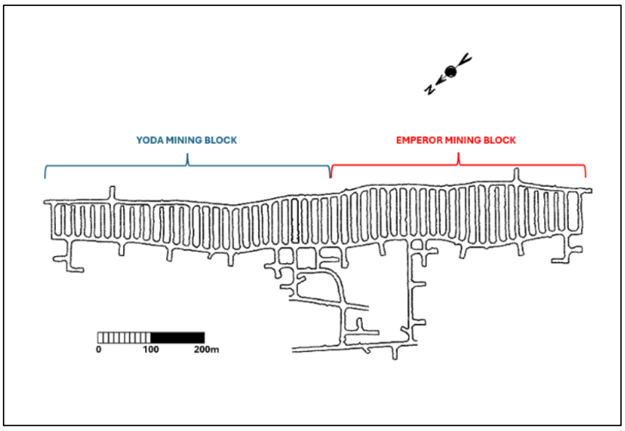

Figure 20 Mining blocks on the 610 level.

6 IMPACTS OF SEISMICITY AT SUG

The impact of seismic events encompasses FoGs with the potential to cause harm and damage to personnel and mine equipment, production delays, increase in costs associated with rehabilitation works and additional ground support requirements as well as impacts on the morale of personnel in the heat of seismic clusters (Esterhuizen, 2018). Two of these impacts as observed at SUG are described below.

6.1 Fall of Ground

Since transitioning from LHOS to SLS, the Subika underground operation has encountered a number of fall of ground (FOG) incidents, primarily concentrated in the SLS slot drive and associated with mining induced seismicity. This trend can be attributed to the relative orientation of the major principal stress to the orebody.

The vast majority of damaging seismicity occurs immediately or shortly after blasting within the SLS, therefore personnel exposure is readily manageable through exclusion zones and periods. However, the occurrence of these failures results in production and mining delays as they necessitate safety risk assessments and rehabilitation efforts.

Figures 21 and 22 depict a fall of ground event on the 585 EMP level, which ensued following three blast-induced seismic events with local magnitudes of 2.1, 1.4, 1.2 and 0.1 after stope blast. Approximately 50 m^3 of rock material was detached from the backs of the heading, restricting mining activities directly above and beneath the damaged area till completion of safety and rehab works.

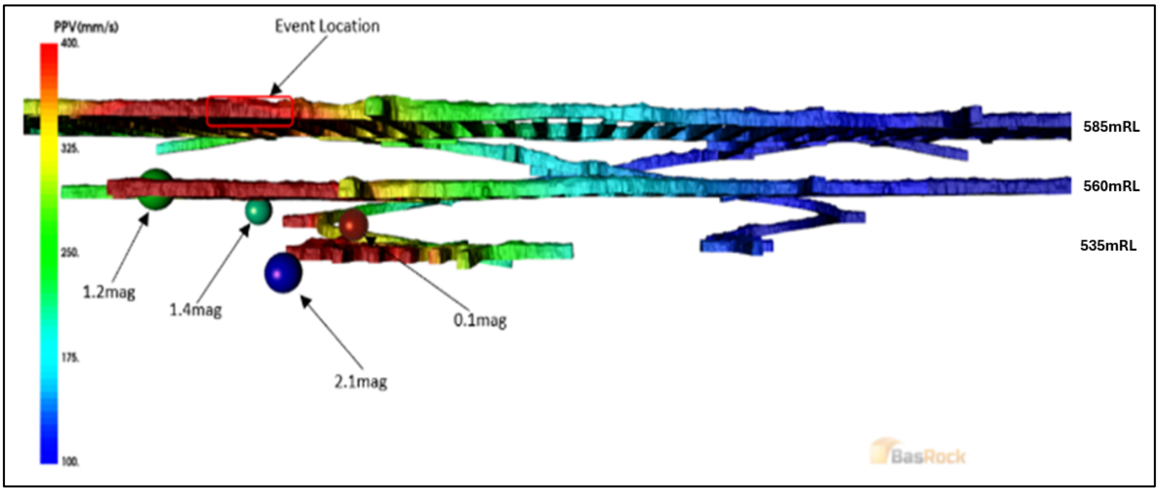

Figure 21 PPV Analysis on Recorded Events That Led to the FoG.

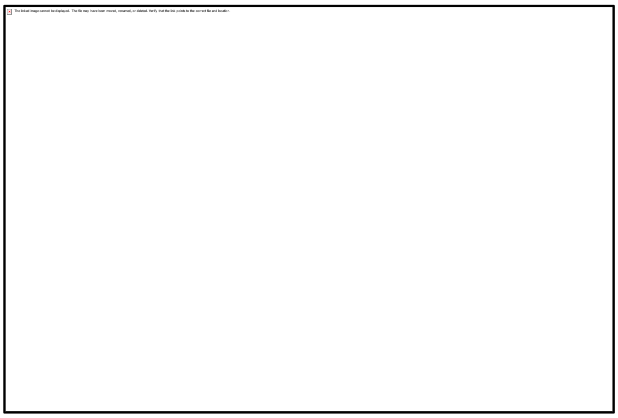

Figure 22 Fall of Ground Event at the 585 EMP Level Slot Drive.

6.2 Production Delays

The interruptions in operations emanating from adherence to post firing seismic exclusion protocols, occurrence of seismic events and FoGs lead to a reduced overall mining efficiency and productivity. Production headings are put on hold after the occurrence of seismic events of significant magnitudes and rehabilitation works are prioritized and completed after FoG before stoping activities resume within affected areas, leading to loss of production hours.

7 MANAGING SEISMICITY AT SUG

Seismicity management at SUG aims to be more proactive than reactive, thus utilizing various protective measures to remove hazards, while adopting just-in time techniques as a last resort. Numerical modelling predicted an adverse stress environment as mining progresses, which could have significant impacts on ground stability. SUG has so far managed seismic hazards through various tactical and strategic means as described below.

7.1 Exclusion Practice

The dynamic stresses from blasts and the adaptation of the rockmass to the new stress conditions after blasting could cause a large seismic event (Güçlü et al. 2020). Some seismic events follow the blast almost immediately, but some can follow in hours. Typical blast times at SUG are between 05:00 - 07:00 and 17:00 - 19:00 hrs. Time of day distribution of current seismic event data as shown in Figure 23 depicts the majority of seismic events occurring within the blasting window, reiterating, the need for seismic exclusion and re-entry protocols before and after blasting.

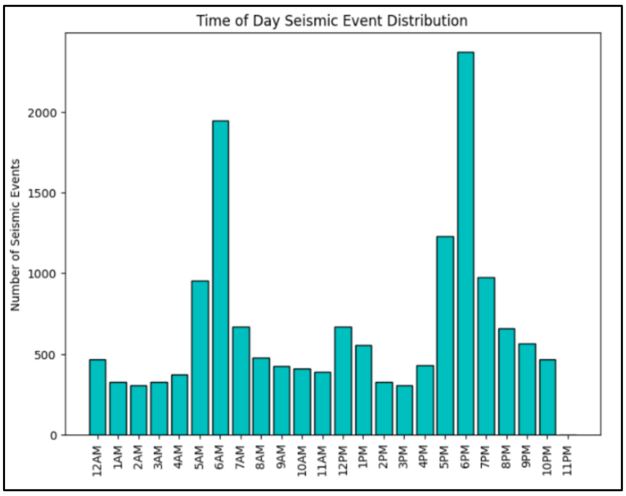

Figure 23 SUG Seismic Event Distribution by Time of Day.

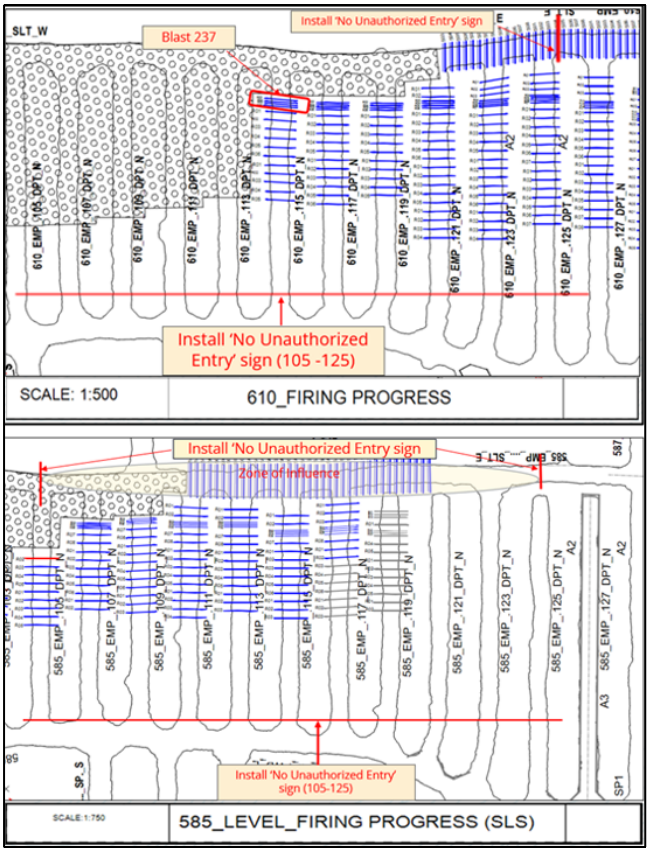

Figure 24 Post Firing Seismic Exclusion Note.

Seismic exclusion and re-entry protocols before and after blast practices are implemented at SUG for slot and breakthrough ring firings, and any other production firing of two (2) or more rings, with exclusion zones set at four drawpoints (60

m) on both sides of the firing location and the level below. Access to the exclusion zone is blocked for a minimum of three (3) hours when a Geotech engineer is on site to conduct a re-entry inspection, and five (5) hours when the Geotech engineer is off site in which case the re-entry inspection is conducted by mine foremen. The re-entry period may extend beyond the minimum hours depending on the ground conditions at the time of inspections. Figure 24 shows an image of a post firing seismic exclusion note issued for a blast.

7.2 Seismic Response Trigger Action Response Plans (TARP)

Seismic Trigger Action Response Plans (TARP) for large events or rockbursts detail the actions, communication and response required in the event of a large seismic event. This includes immediate actions to be taken and reporting, as well as investigations and any remedial actions required. Figure 25 shows an extract of the TARP for seismic events in an active heading at SUG.

TARP FOR LARGE SEISMIC EVENT RECORDED BY SEISMIC SYSTEM

	DAY SHIFT					
Risk Level	Trigger	Minimum Exclusion Zone	Minimum Exclusion Period	Geotech	Operations	Communication Level
Level 1 Low	0.3 ≤ ML < 1.0 within 50 m of mine workings	-	-	1) Review event size and location in Ticker3D. 2) Notify Mine Control that a Level 1 Event has occurred. Communicate magnitude, location, and area to be inpsected. 3) Investigate and assess any damage identified by the Shift Supervisors's inspection and issue recommendation.	1) Mine Control to notify Shift Supervisor that a Level 1 event has occured, the location and areas that require inspecting. 2) Shift supervisor to inspect area for any damage to rock mass and ground support. If any damage is identified, the area is to be barricaded. Shift supervisor to inform Mine Control of findings. 3) Mine Control to note findings and relay to Geotech. 4) If any damage observed - area is to remain barricaded until Geotech assessment and recommendation is issued.	1) Geotech to inform Mine Tech Services Manager and Mine Manager
Level 2 Moderate	1.0 ≤ ML < 1.5 within 100 m of mine workings	40 m radius	3 hours	1) Review event size and location in Ticker3D. 2) Notify Mine Control that a Level 2 Event has occurred. Communicate magnitude, location, and area to be barricaded. 3) Monitor seismic event data in Ticker3D for the exclusion period. 4) If new seismic activity occurs, extend exclusion time, and revise exclusion zone in accordance with the TARP trigger level. 5) When seismicty has returned to background levels, conduct inspection of area of concern, or authorise Foreman to conduct inspection. 6) Geotech to issue recommendation.	1) Mine Control to notify Shift Supervisor that a Level 2 event has occured, the location and areas that require barricading and evacuation. 2) Shift supervisor notifies all personnel in affected area to evacuate to a safe area. 3) Shift supervisor to barricade all affected areas. 4) Foreman to conduct inspection when authorised by Geotech. If any damage is observed - area is to remain barricaded. 5) Foreman to relay findings to Geotech.	1) Geotech to inform Mine Tech Services Manager and Mine Manager and Regional Principal Geotechnical Engineer 2) Mine Manager to inform General Manager
Level 3 High	1.5 ≤ ML < 2.4 within 150 m of mine workings	80 m radius	5 hours	1) Review event size and location in Ticker3D. 2) Notify Mine Control that a Level 3 Event has occurred. Communicate magnitude, location, and area to be barricaded. 3) Monitor seismic event data in Ticker3D for the exclusion period. 4) If new seismic activity occurs, extend exclusion time, and revise exclusion zone in accordance with the corresponding TARP trigger level. 5) When seismicty has returned to background levels, conduct inspection of area of concern. 6) Geotech to issue recommendation.	1) Mine Control to notify Shift Supervisor that a Level 3 event has occured, the location and areas that require barricading and evacuation. 2) Shift Supervisor to notify all personnel in affected area to evacuate to a safe area. 3) Shift Supervisor to barricade all affected areas. 4) Shift Supervisor to report to Mine Control that the affected area has been evacuated and barricades are in place.	1) Geotech to inform Mine Tech Services Manager and Mine Manager and Regional Principal Geotechnical Engineer 2) Mine Manager to inform General Manager
Level 4 Extreme	ML ≥ 2.4 within 200 m of mine workings	Mine Wide	12 hours	1) Review event size and location in Ticker3D. 2) Notify Mine Control that a Level 4 Event has occurred and to inform the Mine Foreman to initiate Mine Evacuation Procedure. 3) Monitor seismic event data in Ticker3D for the exclusion period. 4) If seismic activity is observed, extend exclusion time, and revise exclusion zone as required. 5) When seismicty has returned to background levels, conduct inspection of area of concern. 6) Geotech to issue recommendation.	1) Mine Control to notify the Mine Foreman that a Level 4 event has occured and to initiate the Mine Evacuation Procedure. 2) Mine Foreman to initiate the Mine Evacuation Procedure.	1) Geotech to inform Mine Tech Services Manager and Mine Manager and Regional Principal Geotechnical Engineer 2) Mine Manager to inform General Manager

Figure 25 TARP For Seismic Activity In An Active Heading.

7.3 Dynamic Ground Support

SUG's Ground Support Standards (GSS) are minimum requirements and the specification of a particular GSS is done according to the size, shape, and purpose of the excavation as well as the expected ground support requirement from assessment based on the design process and design margin. GSSs are reviewed when there are changes to ground support suppliers and ground conditions that require a different scheme. Specifications are also sometimes changed depending on ground conditions encountered in development, at the discretion of the Shift Supervisor, Mine Foreman/Captain, Mine Superintendent and/or Geotechnical Engineer.

The primary ground support utilized at SUG consists of friction bolts, resin-encapsulated rebar bolts (24mm diameter), and mesh, with shotcrete being used in highly fractured areas. Due to the short-term nature of the slot drive and drawpoint development, initial ground support comprised only friction bolts and mesh. However due to increased seismic response to SLS mining and rock fall events experienced in slot drives, and damaged brows in the drawpoints, a tighter pattern of bolts was implemented together with the use of higher capacity resin-encapsulated rebar bolts resulting in a significant increase in installed support pressure. Figures 26 and 27 show the current ground support standards utilized in the footwall and hanging wall slot drives at SUG.

While these new support standards have demonstrated enhancements in ground conditions, their effectiveness falls short, particularly in areas prone to seismic events. In such areas, the mesh is seen to blow apart with friction bolts snapping or pulling out depending on the intensity of the seismic event.

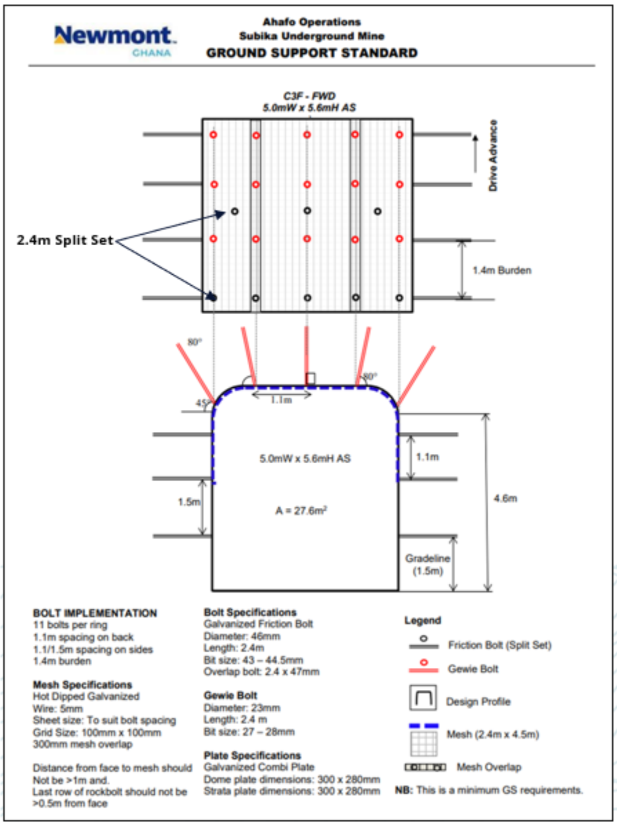

Figure 26 **Current Ground Support Standard in the Footwall Drive.**

Recommendations were made to evaluate the current ground support system to include dynamic support elements that will effectively absorb dissipated energies, minimize the impact of seismicity and possibly eradicate or minimize associated potential rockmass damage. A ground support trial was conducted on Sandvik's Posimix and MDX bolts as well as Epiroc's Par1 yielding bolt shown in Figure 28.

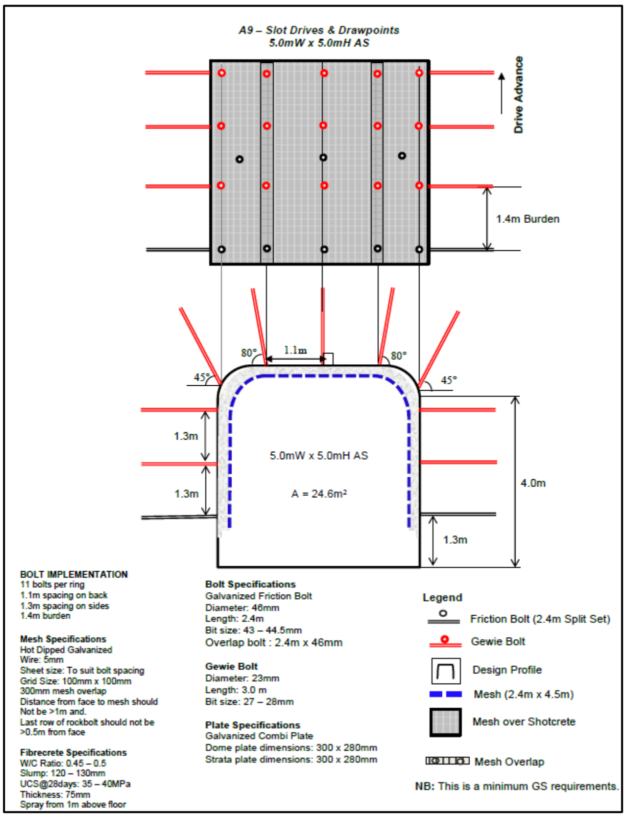

Figure 27 **Current Ground Support Standard in the HW Slot Drive.**

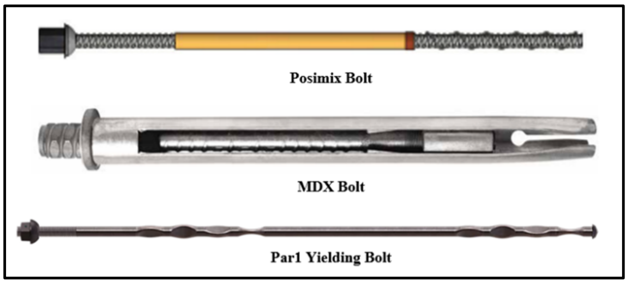

Figure 28 **Dynamic Ground Support Elements.**

Following a thorough analysis, taking into account various factors such as the geotechnical setting of the host rock, empirical and numerical design considerations, and adherence to best industrial practices, the debonded posimix resin bolt from Sandvik was identified as the best fit for purpose while the MDX bolt will be a backup support for seismic prone areas on the mine. The new dynamic supports are scheduled to be integrated into the SUG ground support standard, taking effect from the 535mRL.

7.4 Development and Production Rules

Careful consideration is given to the sequence of mining at SUG due to the high mining induced stresses at play. Development and production sequences are analyzed on a global scale for long-term mine plans; however, detailed review is performed on a short to medium term basis to ensure geotechnical risks are controlled.

Development rules are implemented to protect development excavations, where possible, with the slot drive shadowing the subsequent development (Woods et al., 2018). SLS drawpoints are held at least 8 m short of the slot drive until the slot is developed past the next drawpoints, shadowing the area, before the pillar is broken through as shown in Figure 29.

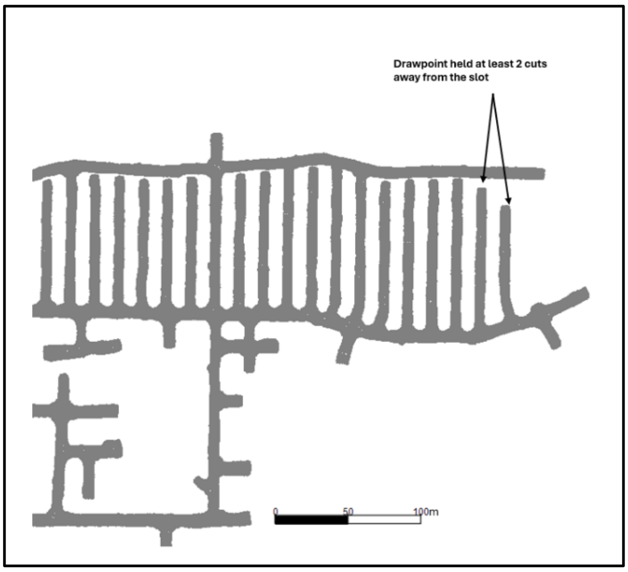

Figure 29 Slot Shadowing at SUG (560 mRL).

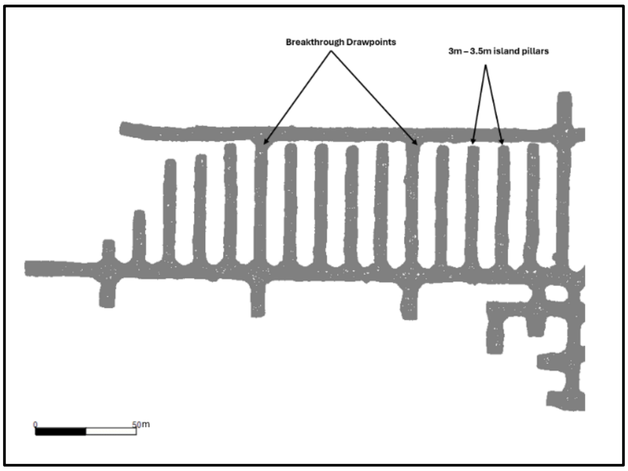

Figure 30 Island Pillar Concept at SUG (560 mRL).

In order to operationally manage the development rules, management adopted the concept of island pillars (see Figure 30) which was aimed at reducing larger spans and ground support consumption in the slot drives. These pillars subsequently allow the slot drive to be fired well in advance of the breakthrough drawpoints.

A chevron mining layout is a common stress control technique adopted at SUG during stoping operations. According to Bawden (2023), this design pushes the stress front towards the solid abutments, eliminating the risk of pillar bursts and providing for more uniform stress conditions on each level. SUG utilizes the chevron approach with a 7.5 m (3 rings lag) lead-lag between adjacent drawpoints while maintaining inter-level production fronts close to 45° as shown in Figures 31 and 32.

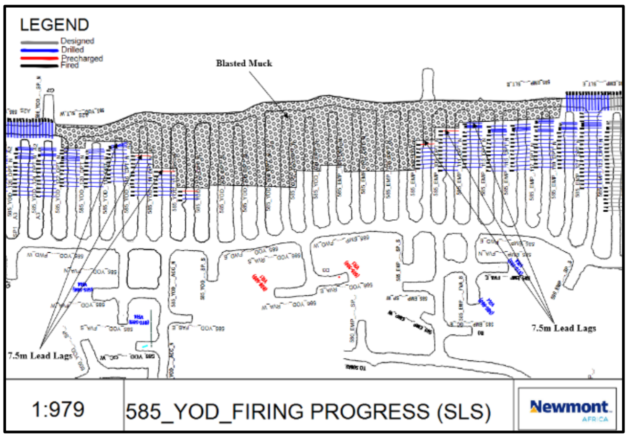

Figure 31 Chevron Mining Approach (585 mRL).

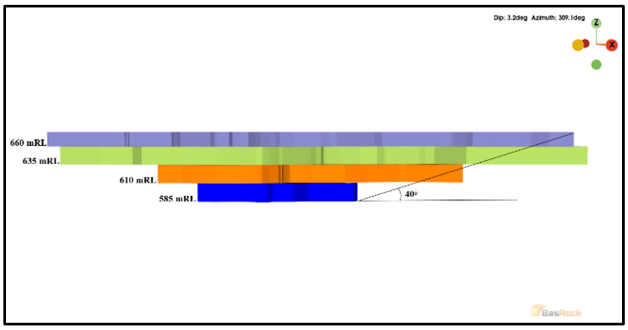

Figure 32 SUG Interlevel Mining Extent Rule (585 mRL).

8 CONCLUSION

The seismic monitoring network at Newmont's Subika Underground Mine is instrumental in ensuring that all stakeholders are promptly informed of seismic events in real time, allowing for appropriate and timely responses. The implementation of the TARP and a comprehensive seismic management plan has been vital in managing seismic hazards, thereby significantly enhancing the safety and risk mitigation measures at the mine. This paper discusses the challenges of seismic activity in underground mining, particularly in sub-level shrinkage mining areas, and provides insights into the reasons for mining method changes, post-change infrastructural activities, seismic event mechanisms, and mitigation strategies three years into operations. Dynamic stresses induced by blasts can lead to seismic events, emphasizing the importance of seismic exclusion and re-entry protocols, along with Seismic Trigger Action Response Plans (TARPs), to ensure personnel safety and mitigate seismic impact. Ground support standards, including dynamic support elements, have evolved to minimize rockmass damage in seismic-prone areas. Development and production rules, such as slot shadowing, chevron mining sequence and island pillars, further manage geotechnical risks. These strategies demonstrate SUG's commitment to safe and efficient mining practices in challenging geotechnical environments.

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