Seismicity Evolution And Rockburst Control In The Merensky Reef And UG2 Orebody: An Intermediate-depth Platinum Mine Case Study

R.T. Masethe[1]*, S. Durapraj[2], U. Maqina[2] and A. C. Adoko[3]

[1]School of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Durban, South Africa.

[2]Rock Engineering Department, Sibanye Stillwater PGM, Rustenburg, South Africa.
[3]School of Mining and Geoscience, Nazarbayev University, Astana 010000, Kazakhstan.

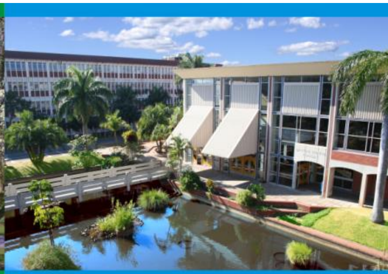
Journal of the Southern African Institute of Mining and Metallurgy, vol. 125, no. 1, pp. 51–60


EDGEWOOD CAMPUS


HOWARD COLLEGE CAMPUS


NELSON R MANDELA SCHOOL OF MEDICINE


PIETERMARITZBURG CAMPUS


WESTVILLE CAMPUS

UKZN INSPIRING GREATNESS

Motivation of the Study

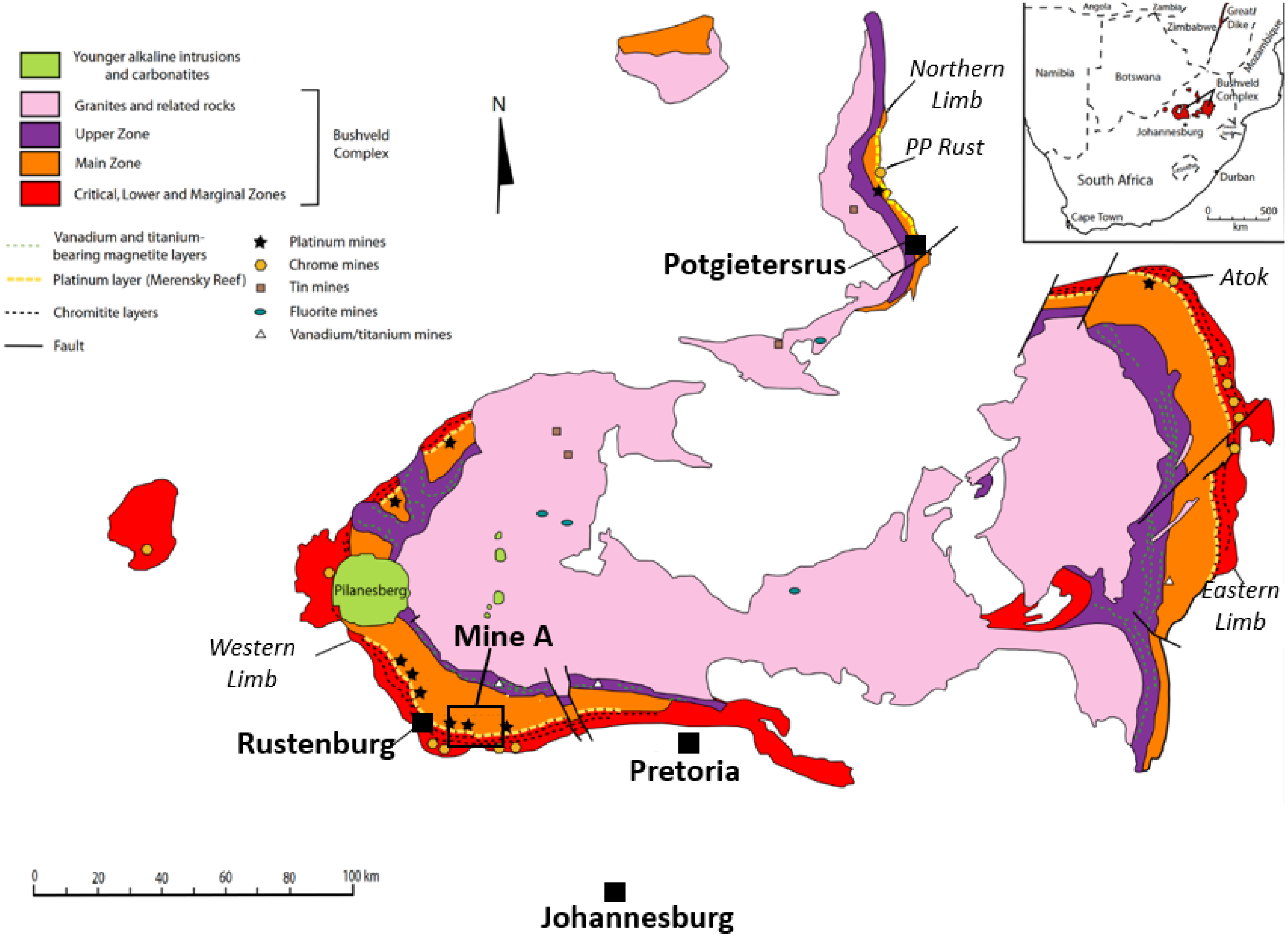
- Understand the evolution of seismicity in the Merensky Reef and UG2 orebody.
- Enhance safety through improved support designs and seismic monitoring.
- Develop predictive tools for assessing and mitigating rockburst risks, ensuring operational efficiency and personnel safety.

Methodology

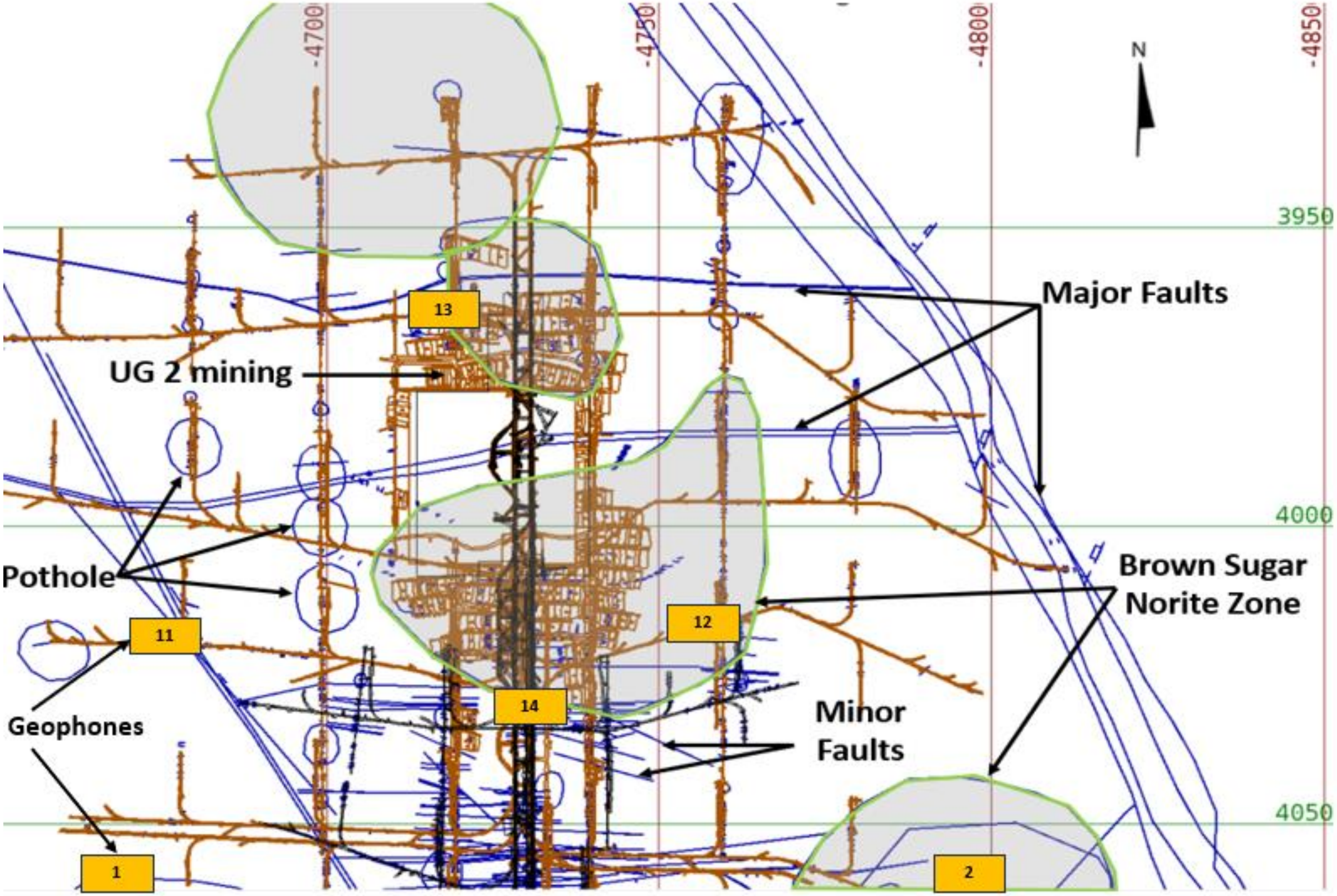
- Seismic monitoring using a network of **9** tri-axial geophones that recorded over 1,900 events with advanced analyses,
- Moment Tensor Inversion for **failure mechanisms** and the **Rockburst Damage Potential (RDP)** method used to assess **rockburst risk**.
- The study also evaluated and redesigned rock support systems to enhance resilience under quasi-static and dynamic seismic conditions.

A support system evaluation analysed existing and redesigned rock support systems for quasi-static and dynamic conditions to improve resilience against seismic events.

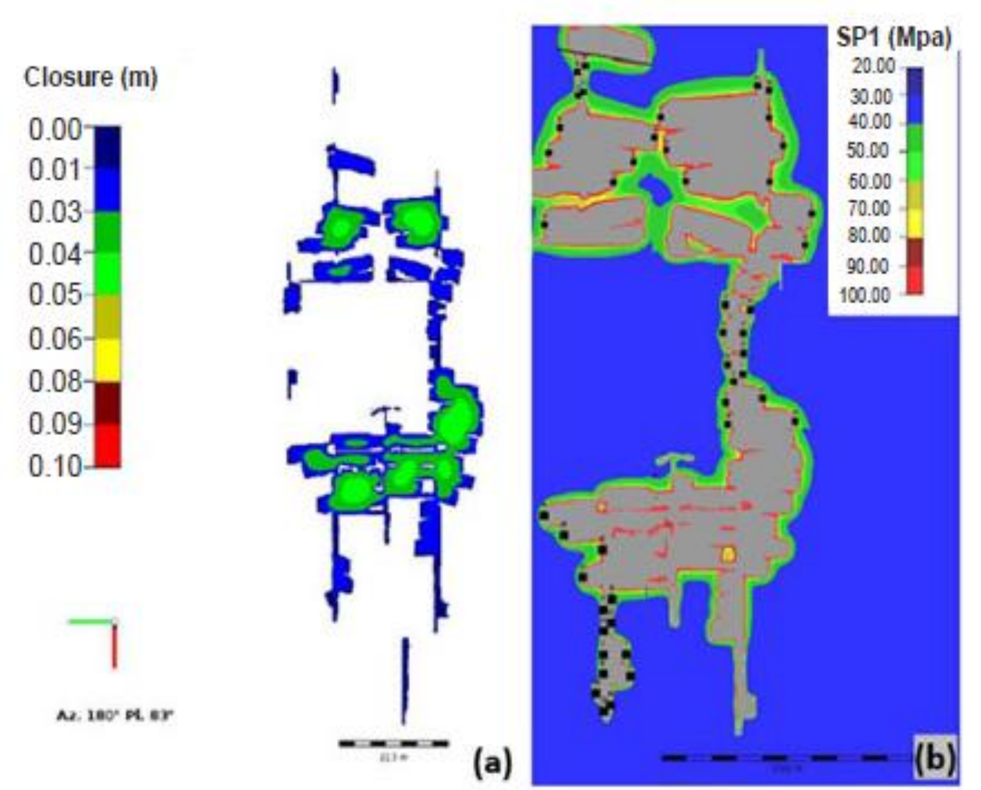
Geological map of the Bushveld Igneous Complex (BIC)



The mine plan, current mining, location of closer geophones, and the region of brown sugar norite (BSN) in green

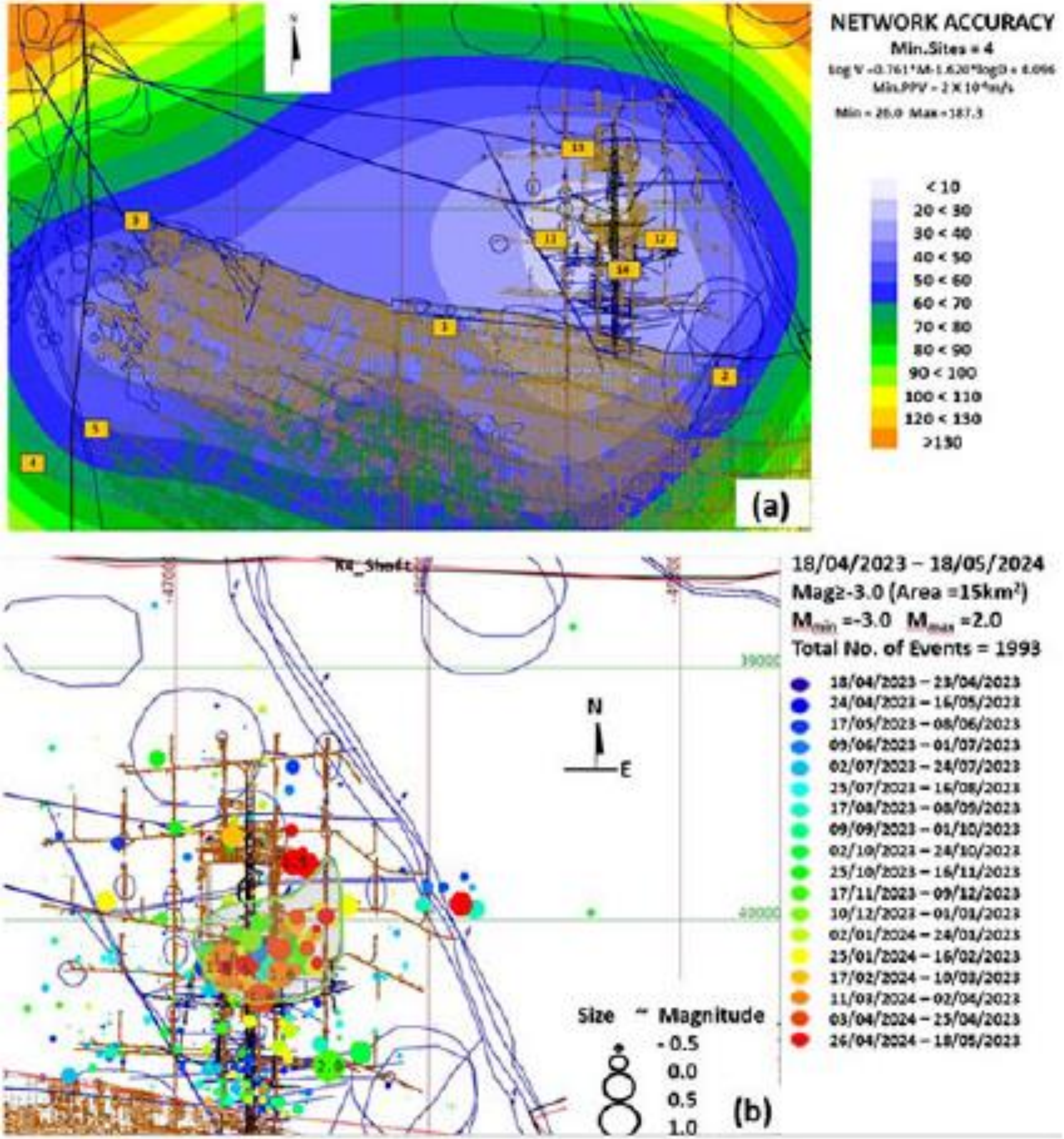


Mining Environment Characterization



The medium mining depth environment is associated with:

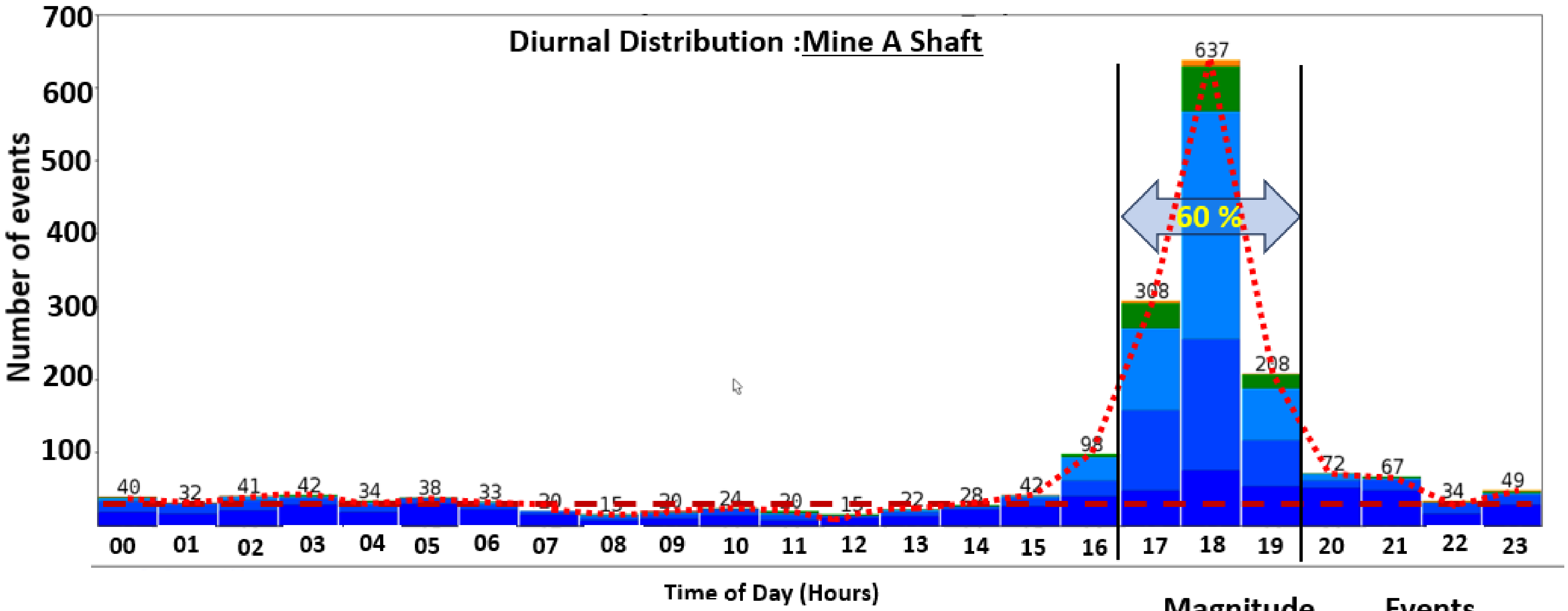
- ☐ **vertical stress states between 47-94 MPa**
- ☐ **moderate stress fracturing**
- ☐ **moderate stope closure (~10-30mm/m face advance)**
- ☐ **moderate to severe rock burst hazard.**



(a) Modelled seismic location accuracy which is deemed adequate for location and long-term strategic planning.

(b) Spatial distribution of seismicity and geological structures

Diurnal distribution



18/04/2023 – 18/05/2024

All seismic events of Mag≥-3.0

M_{min} =-3.0 M_{max} =2.0

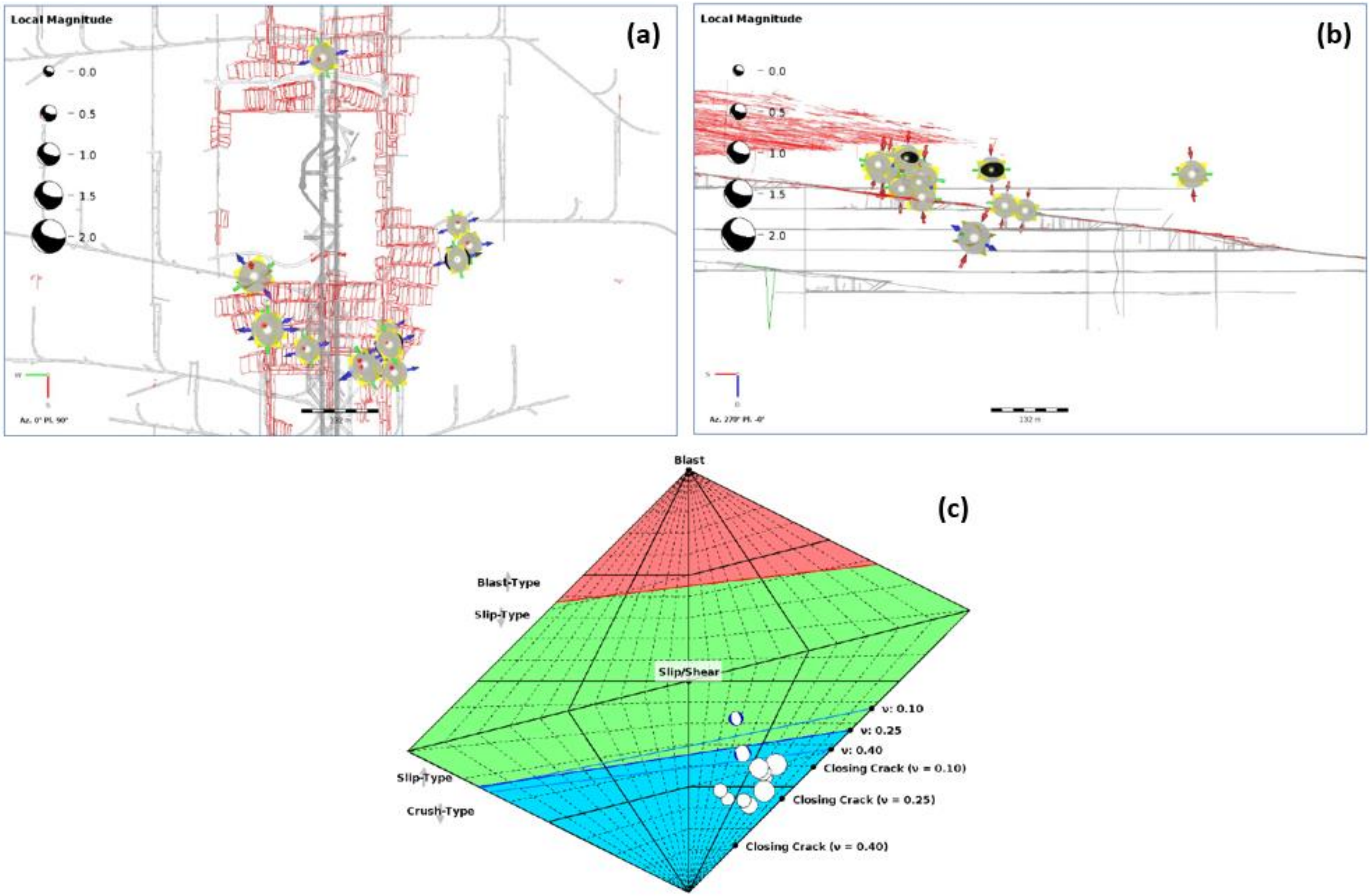
Total number of events = 1993

	Magnitude	Events
🟦	-3.0≤M<-2.0	625
🟦	-2.0≤M<-1.0	561
🟦	-1.0≤M<0.0	580
🟩	0.0≤M<1.0	145
🟧	1.0≤M<2.0	27
🟥	M≥2.0	1

Spatial distribution of seismicity

The mine seismic system recorded 1,993 ML ≥ -3.0 seismic events between April 18, 2023, and May 18, 2024:

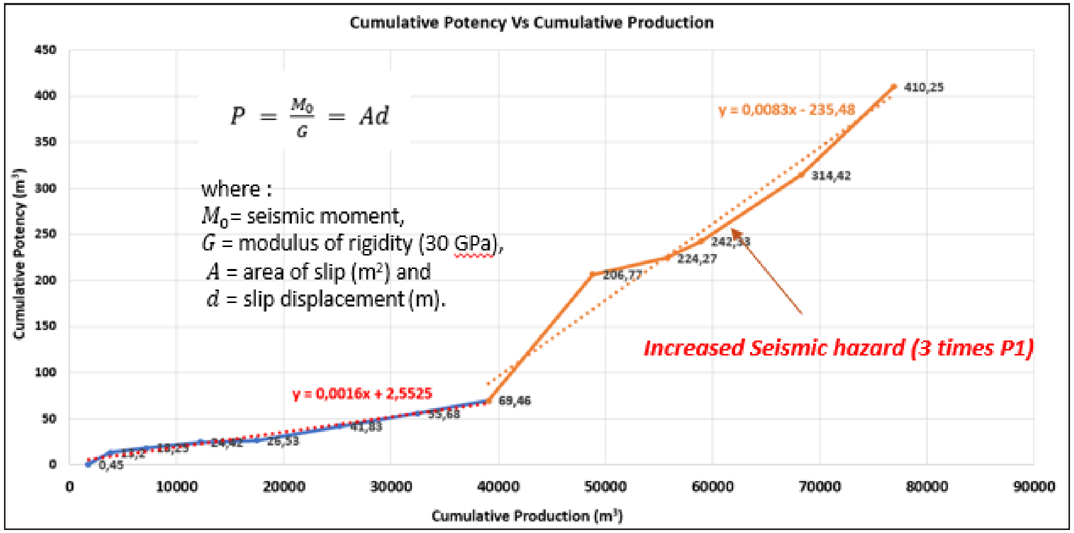
- The **Largest seismic event** was **M_L ≥2.0**, located on or very close to the reef plane and **associated geological structures**.
- **Ninety percent** (90%) of the $M_L \geq 0.0$ seismic events are located within the **brown sugar norite zone**.
- Of the **27** seismic events with **$1.0 \leq M_L < 2.0$** located in, or very close to, the reef plane, **70%** correlate with **pillar foundation failure** and **bursts**, and **30%** are associated with other **mining elements**.
- Of the **431** seismic events that have **$0.0 \leq M_L < 1.0$**, **75%** are associated with **pillar bursts,** and the remaining **25%** are a mix of events associated with **geological features**, **pillar failures**, and/or **pillar foundation failures.**
- **1,535** seismic events have **$-3.0 \leq M_L < 0.0$**. They are primarily located within active stopes faces. These small events also pose a risk to workers, since **preconditioning has not yet been implemented**.



- The predominant failure mode in the area of interest was the closure of apertures. This suggested that, while stope closure might have played a significant role, the seismic source mechanisms were more obviously indicative of stress-driven fracture closure.

- These mechanisms are typically associated with **dynamic pillar failure** and **stope closure**. These are consistent with the underground observation of dynamic closure on support units.

Seismic response to production analysis



$$P = \frac{M_0}{G} = Ad$$

where :
M_0 = seismic moment,
G = modulus of rigidity (30 GPa),
A = area of slip (m²) and
d = slip displacement (m).

Increased Seismic hazard (3 times P1)

Seismic Potency versus production indicating the change in the seismic response of the rock mass to mining from period P1 (1/3/2023 - 1/10/2023) to period P2 (1/11/2023-31/3/2024))

Seismic Potency versus Production

	P1 (1/3/2023 - 1/10/2023 = 8 months)		P2 (1/11/2023-31/3/2024) = 5 months)	
	Production (m³)	Potency (m³)	Production (m³)	Potency (m³)
Monthly	6 350.6	8.7	7 571.6	68.2
Quarterly	25 403.8	34.7	37 858.0	2 586.1
Total	50 806.6	69.5	101 613.3	340.8
P:V$_m$	0.001		0.003	

Period 1: This period spans **248 days** and contains **4** $M_L \geq 1.0$ seismic events, **69 $M_L \geq 0.0$** seismic events, and **580 $M_L \geq -3.0$** events. The volume-mined is 50.8 x 10³m³ and the cumulative seismic potency is **5.6 x 10³ m³;** the ratio of volume-mined to seismic potency is thus $\sum P/V_m$ = **0.001**. The largest seismic event occurred on **17 May 2023** with **M_L= 1.1.**

Period 2: This period has spans of **150 days** and contains **1** $M_L \geq 2.0$ seismic events**, 17 $M_L \geq 1.0$** events **82 $M_L \geq 0.0$** events and 935 $M \geq -3.0$ events. The volume-mined is **101.6 x 10³ m³** and the cumulative seismic potency is 340.8 m³. The ratio of cumulative seismic potency to volume-mined for Period 2 is $\sum P/V_m$ = **0.003**, almost three times the ratio in Period 1, **indicating an increase seismic hazard in the Mine A** area. The largest seismic event occurred on **19 November 2023** with **M_L= 2.0.**

Steeper Seismic Potency Slope indicates an increase in Hazard

P2 (0,003) is more hazardous than P1(0,001)

Rockburst risk analysis using the Rockburst Damage Potential (RDP) approach

- Grout Pack on 3.0 m x 3.0 m pattern.
- 1.6 m long resin bolt on a 1.5 m x 1.5 m pattern.
- 1.5 m long full-column grouted tendon on a 1.5 m x 1.2 m pattern (gully support).
- Temporary mechanical prop on a 1.5 m - 2.0 m pattern.
- 2.0 m wide safety net on the stope face area’s hanging wall.

The redesigned support system in this area to mitigate the risk of rockburst now comprises:

- Grout Pack on 8.0 m (strike) x 4.0 m (dip) pattern (center to center).
- 1.6 m long resin bolt on a 1.5 m x 1.5 m pattern (in the stope hangingwall in the face area).
- 1.5 m long full column grouted tendon on a 1.5 m x 1.2 m pattern (gully support).
- 1.5 m long yielding prestressed elongate (timber and steel elongate) on a 1.5 m (dip) x 2.0 m (strike) spacing (center to center).
- Temporary mechanical prop on a 1.5 m x 2.0 m pattern.
- 2.0 m wide safety net on the stope face.

Rockburst risk analysis using the rockburst damage potential (RDP) approach

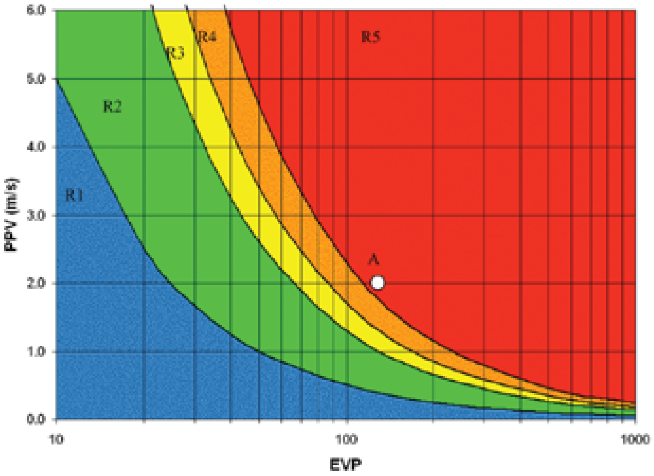
- The method for assessing excavation vulnerability and rockburst damage potential, developed by Heal et al. (2006), has been adapted and applied

- It is a method based on **83 case histories** with **254** damage locations from **13 Australian and Canadian mines**. Heal et al. (2006) proposed the rock damage scale (RDS). RDP is a function of the excavation vulnerability potential (EVP) and peak particle velocity (PPV) that an empirical chart can represent in a probabilistic sense.

Rockburst risk analysis using the rockburst damage potential (RDP) approach

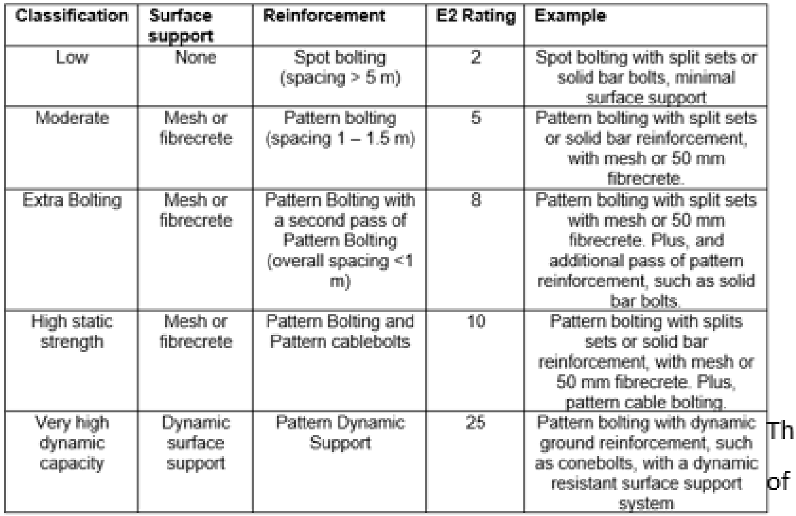
Rockburst Damage Scale (after Heal et. al., 2006)

Rockburst Damage Scale	Rockburst Damage	Support Damage
R1	No damage, minor loose	No damage
R2	Minor damage, less than 1 tonne displaced	Support system is loaded, loose in mesh, plates deformed
R3	1 – 10 tonnes displaced	Some broken bolts
R4	10 – 100 tonnes displaced	Major damage to support system
R5	100+ tonnes displaced	Complete failure of support system



Empirical chart relating the PPV to the EVP to assess the RDP (R1 to R5) (After Heal 2006)

Support capability in rockburst situations (after Heal et al., 2005)



Classification	Surface support	Reinforcement	E2 Rating	Example
Low	None	Spot bolting (spacing > 5 m)	2	Spot bolting with split sets or solid bar bolts, minimal surface support
Moderate	Mesh or fibrecrete	Pattern bolting (spacing 1 – 1.5 m)	5	Pattern bolting with split sets or solid bar reinforcement, with mesh or 50 mm fibrecrete.
Extra Bolting	Mesh or fibrecrete	Pattern Bolting with a second pass of Pattern Bolting (overall spacing <1 m)	8	Pattern bolting with split sets with mesh or 50 mm fibrecrete. Plus, and additional pass of pattern reinforcement, such as solid bar bolts.
High static strength	Mesh or fibrecrete	Pattern Bolting and Pattern cablebolts	10	Pattern bolting with splits sets or solid bar reinforcement, with mesh or 50 mm fibrecrete. Plus, pattern cable bolting.
Very high dynamic capacity	Dynamic surface support	Pattern Dynamic Support	25	Pattern bolting with dynamic ground reinforcement, such as conebolts, with a dynamic resistant surface support system

$$E1 = 100\,x\,\frac{\sigma_1}{UCS}$$

where σ_1= the major principal stress and UCS is the Uniaxial Compressive Strength

excavation vulnerability potential

$$EVP = \frac{E1}{E2}\,x\,\frac{E3}{E4}$$

Where E1 represents a stress -to -strength ratio, E2 a support capability, E3 excavation span and E4 the Geological factor

$$PPV = 1.4\frac{10^{\frac{M_r}{2}}}{r}$$

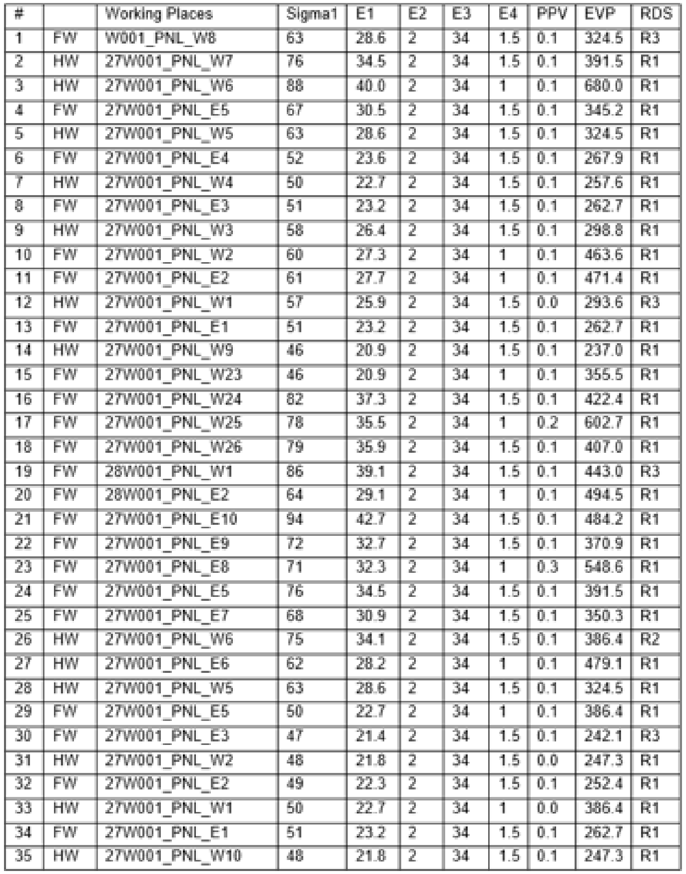
where M_r represent a seismic event magnitude and r *being* the distance between the hypocentre and the experience damage

$$RDP = EVP \times PPV$$

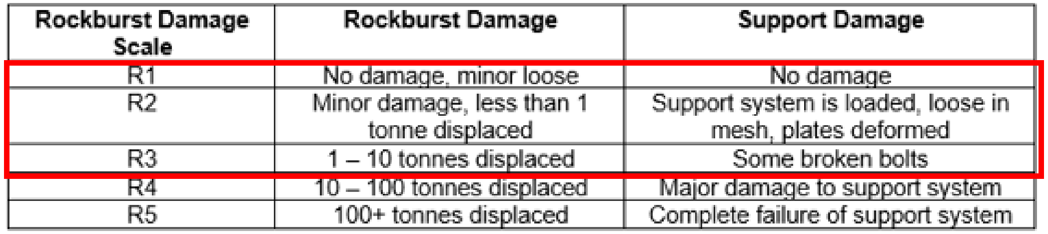
The RDP is the probability of occurrence of a rockburst of a given scale (Heal et al 2006).

RDP is a function of the excavation vulnerability potential (EVP) and peak particle velocity (PPV) that can be represented by an empirical chart in a probabilistic sense)

Rockburst damage potential (RDP) data



#		Working Places	Sigma1	E1	E2	E3	E4	PPV	EVP	RDS
1	FW	W001_PNL_W8	63	28.6	2	34	1.5	0.1	324.5	R3
2	HW	27W001_PNL_W7	76	34.5	2	34	1.5	0.1	391.5	R1
3	HW	27W001_PNL_W6	88	40.0	2	34	1	0.1	680.0	R1
4	FW	27W001_PNL_E5	67	30.5	2	34	1.5	0.1	345.2	R1
5	HW	27W001_PNL_W5	63	28.6	2	34	1.5	0.1	324.5	R1
6	FW	27W001_PNL_E4	52	23.6	2	34	1.5	0.1	267.9	R1
7	HW	27W001_PNL_W4	50	22.7	2	34	1.5	0.1	257.6	R1
8	FW	27W001_PNL_E3	51	23.2	2	34	1.5	0.1	262.7	R1
9	HW	27W001_PNL_W3	58	26.4	2	34	1.5	0.1	298.8	R1
10	FW	27W001_PNL_W2	60	27.3	2	34	1	0.1	463.6	R1
11	FW	27W001_PNL_E2	61	27.7	2	34	1	0.1	471.4	R1
12	HW	27W001_PNL_W1	57	25.9	2	34	1.5	0.0	293.6	R3
13	FW	27W001_PNL_E1	51	23.2	2	34	1.5	0.1	262.7	R1
14	HW	27W001_PNL_W9	46	20.9	2	34	1.5	0.1	237.0	R1
15	FW	27W001_PNL_W23	46	20.9	2	34	1	0.1	355.5	R1
16	FW	27W001_PNL_W24	82	37.3	2	34	1.5	0.1	422.4	R1
17	FW	27W001_PNL_W25	78	35.5	2	34	1	0.2	602.7	R1
18	FW	27W001_PNL_W26	79	35.9	2	34	1.5	0.1	407.0	R1
19	FW	28W001_PNL_W1	86	39.1	2	34	1.5	0.1	443.0	R3
20	FW	28W001_PNL_E2	64	29.1	2	34	1	0.1	494.5	R1
21	FW	27W001_PNL_E10	94	42.7	2	34	1.5	0.1	484.2	R1
22	FW	27W001_PNL_E9	72	32.7	2	34	1.5	0.1	370.9	R1
23	FW	27W001_PNL_E8	71	32.3	2	34	1	0.3	548.6	R1
24	FW	27W001_PNL_E5	76	34.5	2	34	1.5	0.1	391.5	R1
25	FW	27W001_PNL_E7	68	30.9	2	34	1.5	0.1	350.3	R1
26	HW	27W001_PNL_W6	75	34.1	2	34	1.5	0.1	386.4	R2
27	HW	27W001_PNL_E6	62	28.2	2	34	1	0.1	479.1	R1
28	HW	27W001_PNL_W5	63	28.6	2	34	1.5	0.1	324.5	R1
29	FW	27W001_PNL_E5	50	22.7	2	34	1	0.1	386.4	R1
30	FW	27W001_PNL_E3	47	21.4	2	34	1.5	0.1	242.1	R3
31	HW	27W001_PNL_W2	48	21.8	2	34	1.5	0.0	247.3	R1
32	FW	27W001_PNL_E2	49	22.3	2	34	1.5	0.1	252.4	R1
33	HW	27W001_PNL_W1	50	22.7	2	34	1	0.0	386.4	R1
34	FW	27W001_PNL_E1	51	23.2	2	34	1.5	0.1	262.7	R1
35	HW	27W001_PNL_W10	48	21.8	2	34	1.5	0.1	247.3	R1

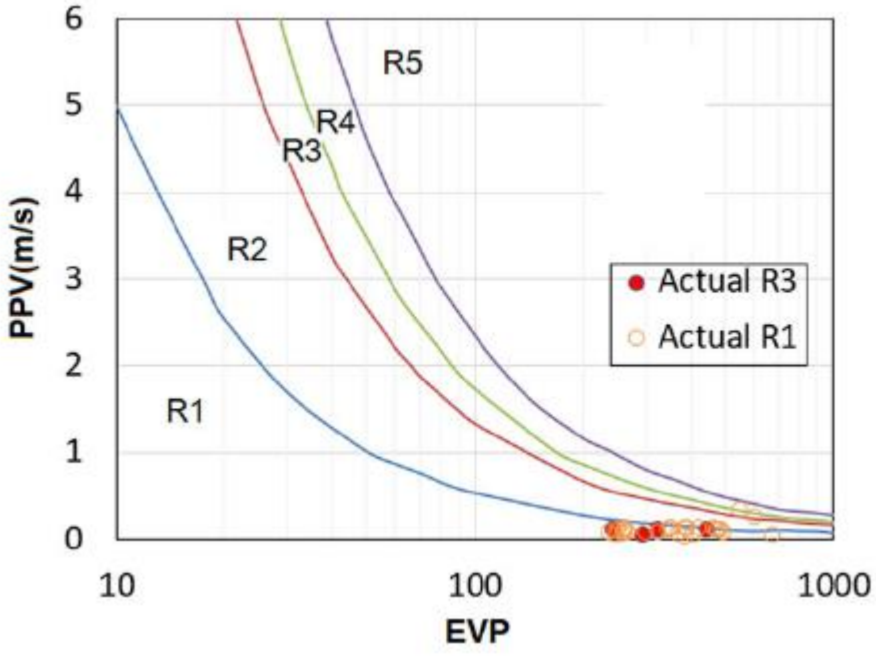


Rockburst Damage Scale	Rockburst Damage	Support Damage
R1	No damage, minor loose	No damage
R2	Minor damage, less than 1 tonne displaced	Support system is loaded, loose in mesh, plates deformed
R3	1 – 10 tonnes displaced	Some broken bolts
R4	10 – 100 tonnes displaced	Major damage to support system
R5	100+ tonnes displaced	Complete failure of support system

RDS	RDS# (27L)	% Total Study
R1	30	86%
R2	1	3%
R3	4	11%

Rock Damage Scale(RDS)

The parameters E1, E2, E3, E4, and PPV were determined according to the RDP method. The EVP was calculated for each rockburst instance. Then, each data point (EPV, PPV) was superimposed to produce the graph the graph below, which shows the predicted RDS for the data. It indicates the probability of rockburst damage scale (R1 to R5) for a given EVP and PPV



Rock Damage Scale(RDS)

- It can be seen that Previous does not show any clear separation of the data according to each zone (R1 to R5), and most of the data points, including those corresponding to R3, fall within the R1 rockburst damage scale.
- This might be due to insufficient data points or bias in the data selected.
- In conclusion, the **RDP** may not be suitable for these **mine conditions**.
- While the RDP has shown to be directly applicable to tunnels and shafts, it might not be directly applicable to intermediate or deep tabular stoping methods
- However, it provides a valuable tool for comparative purposes.
- In the long term, a similar research programme should be implemented to develop a more rigorous risk assessment system directly applicable to deep tabular stoping. Implementing the current system is the onset of this process.

In addition to the seismic assessments, several learnings emanated from the seismic ‘storm’ of the period under review.

These were that the shaft-based geotechnical department had to institute additional measures to:

- Avoid mining irregular or oversized pillars, as these pillars are a source of seismic activity.
- Ensure compliance to pillar-cutting standards, as these were perceived to be the source of a significant number of the 1,993 events; compliance is crucial for managing mine-induced seismicity.
- Include a number of yielding support elements to assist with the yield required in the system.
- Sequence the extraction in such a manner that will reduce the potential seismicity from poor configurations.
- Provide systems to adequately assess seismic incidents, generate trend analyses in real-time, and provide recommendations to underground personnel prior to them starting their shifts.

Learning in the Mine A Shaft: Data and Observations:

- Avoid mining irregular or oversized pillars, as these pillars are a source of seismic activity.
- Pillar-cutting compliance is crucial for managing mine-induced seismicity.
- Incorporation of yielding support elements may aid in creating a “softer” system as opposed to the current “stiff” system.
- Need to avoid stress accumulation as best as possible through design and mine sequencing strategies (incorporated into our planning activities).

Mitigation strategies to be implemented on ground support and the execution plan within the mine are:

- Mining plan execution (Mine design and layout)
- Stop and remediate pillars identified as oversized or irregular.
- Issue Stop Notes for mining without Pillar Cutting Survey Notes.
- Ensure the mining team mines sidings to the design depth of 3.7 m from the center line.
- Enforce self-stoppage if the survey department does not install highway (2.5 m from pillar position) line pegs timeously.
- The mining team will blast pillar holdings in the correct position as per the Survey Note.
- Seismic incident and stope risk analysis to reasonably indicate the potential risk.

Ground support (Support design and implementation) and instrumentations:

- Incorporate yielding props in the stope faces.
- Technically assess the requirement of a yielding pack.
- Continuous seismic monitoring and assessment and configuration of the seismic network should be reviewed.
- To quantify stresses, 3D computational inelastic models (e.g., FLAC3D and UDEC) should be utilized as a continuing monitoring tool, along with a closure recorder and strain meters.

Conclusions

- The seismic database collected for 13 months has proved invaluable in understanding the seismic response to mining within this mine. The evaluation of this seismic response was carried out using seismic statistical hazard parameters and production
- The shaft regularly reviews risk mitigation measures. The study indicates that the seismic hazard (slope of cumulative seismic potency versus cumulative production) has increased during period P2 (1/11/2023 – 31/3/2024). An increase in the gradient of the slope indicates an increase in hazards.
- Peak particle velocity and excavation vulnerability potential index were correlated. A method to assess rockburst risk, namely rockburst damage potential (RDP) indicates that the damage falls within the R1 and R3 rockburst damage scales.
- The Mmax value of 2.0 is higher for Period 2 than the Mmax of 1.1 during Period 1. Regarding seismic event statistics, 100 events of M ≥ 0.0 indicated more instability for Period 2.

Conclusions

- However, the underlying causes of these alterations during the extraction process may stem from various factors, such as the pillar size and the geomechanical properties of the rock mass, especially the unknown rock characteristics of the brown sugar norite (BSN)
- These factors necessitate thorough investigation and will be incorporated into future research endeavours.
- This investigation will allow the rock engineering practitioner to have sight of the influence of production data and production rate increases on seismic potency and, in addition to that, infer the potential for rockburst hazards, develop a rockburst hazard forecast, and use rockburst control techniques to reduce the risk.

THANK YOU!

NAZARBAYEV UNIVERSITY

we are one
Sibanye Stillwater

UNIVERSITY OF KWAZULU-NATAL™
INYUVESI YAKWAZULU-NATALI