Dynamic response of the rock mass where the orebody dip changes

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ABSTRACT: Mining at depth in a South African gold mine, poses common risks and hazards. Many seismic events have, in the past and present, resulted in the loss of life of several employees. Most of these were inexplicable, and no consideration was given in any study where the orebody being normally weaker in relation to the surrounding rock mass is a result of a catastrophic event, merely by the change in its dip. From the investigations it was deduced that when there is a change in the dip of the orebody the surrounding rock mass characteristics allow the orebody to behave in a similar manner as a steeply dipping fault. The following is an attempt to set the scene, analyze and draw conclusions when an orebody dip changes and thus ensuring the transfer of knowledge.

Keywords: Dynamic, response, rock, orebody, dip, change.

1 INTRODUCTION

Mining conventionally in a Deep South African gold mine poses various risks and hazards. These hazards, including rock burst/falls, increased seismic activity, high stresses resulting in fracturing, losses of life, release of heat, etc., thus make mining challenging. Seismicity is normally associated with geological structure, abutment failures and localized face bursting. On 21 October 2021, a rock burst resulted in the loss of life of 2 persons and injuring 4 others. A need arose to assess and evaluate the circumstances when mining in close proximity to a steeply dipping orebody (reef) where the dip changes steeply from the norm of $\sim 26^0$. The incident then initiated a retrospective analysis of previous incidents, with the resulting insights and correlations leading to amelioration strategies.

2 OVERVIEW

2.1 Location and orebody mined

The operation is located 90km from the city of Johannesburg, Gauteng, South Africa and is situated on the far Southern section of the West Rand goldfields. It forms part of the greater Witwatersrand basin and mining is focused on the Ventersdorp Contact Reef (VCR). This is a conglomerate reef band, striking north 65^0 east and dipping 26^0 south. Consisting of various terraces separated by slopes, all of which may be structurally deformed by duplicated reef zones. Value is highly variable and the reef is characterized by a large amount of faulting with throws of less than 10 meters.

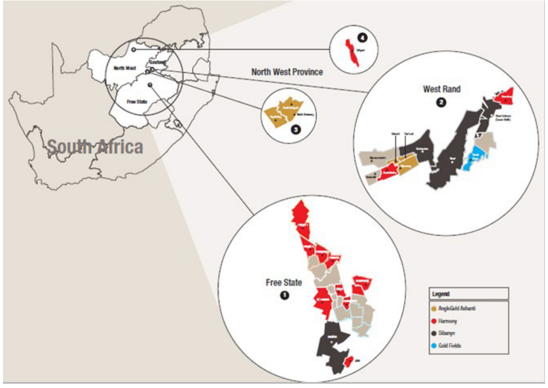


Figure 1. Location within the bounds of South Africa.

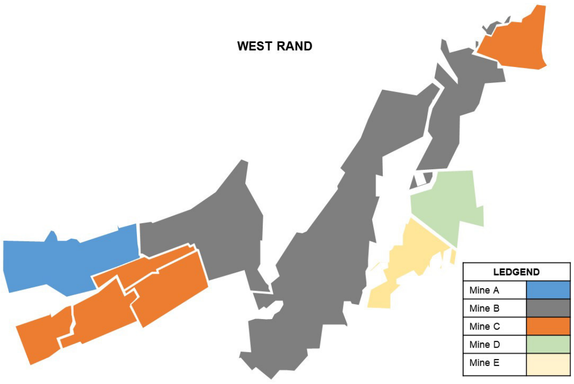


Figure 2. Operation represented as "Mine C".

The hanging wall comprises of Ventersdorp Lavas, with a Uniaxial Compressive Strength (UCS) of ±300MPa. Conditions may vary considerably across the VCR, caused mainly by pilloids; inter pilloids breccias and joints associated with slopes. Other factors include large numbers of flat faulting, which extend into the hanging wall, which is brittle in nature. The footwall host rock compromises of fairly competent quartzite, (UCS 180 – 250Mpa) extending for ~ 450 meters below reef, enabling haulages and primary related development to be sited in this competent footwall rock.

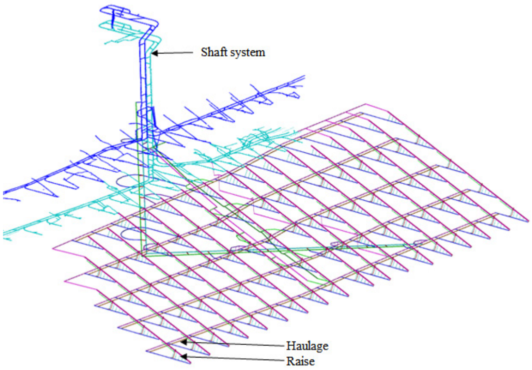


Figure 3. Depiction of the mine infrastructure.

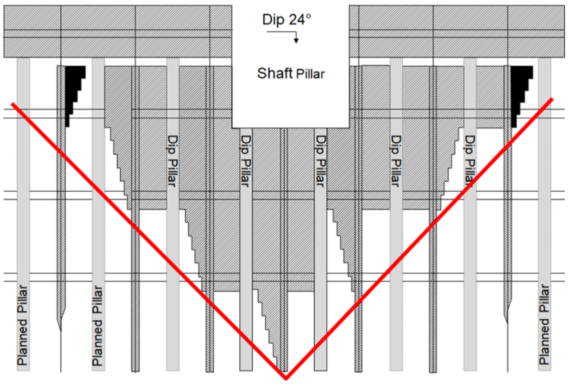


Figure 4. Sequential grid mining method.

2.1.1 *Mining method*

Operational infrastructure (Figure 3) is serviced by 4 surface and 6 sub-verticle shafts for a depth of 3500m from surface. The mining method historically used is a sequential grid mining extraction (Figure 4) where raise lines are spaced 200m apart on strike, separated by 30m wide regional stability dip pillars. Face lengths of 30m, are mined at $+5^0$ above strike. With strike lengths of ~ 85m on either side of the raise, with back lengths of ~ 300m. Mining depth is from 3000m to 3300m below surface.

2.1.2 *Support regime*

Face area support comprises of temporary mechanical props, permanent in-stope blast on netting, tendons, pre-stressed timber elongates, timber packs as shoulder support and classified tailings backfill as back area support. Support units are designed for dynamic loading and work as a system.

3 SEISMIC HISTORY

A seismic system supplied by IMS (Integrated Mining Seismology) is installed, which is monitored continuously. Utilizing an outsourced service provider, ensures the following are maintained: software & hardware maintenance, upgrades, technical support and overall system administration. The system comprises of 34 geophones located ~10m in the footwall and 130m below the reef. The system location error for a 0.0ML is ~ 15m - 30m and sensitivity accuracy of negative 1.5ML. On average 9500 events are recorded per month. The moment tensor of majority of the events analyzed has a strong slip component with a small burst-type component.

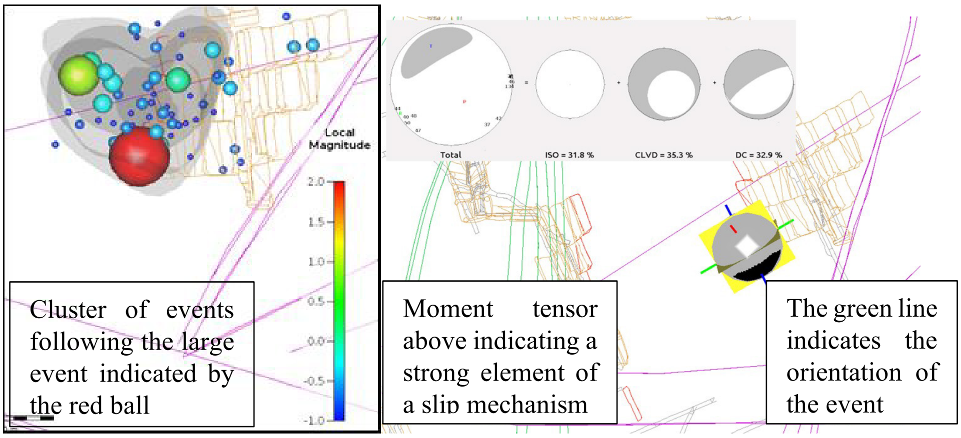
An average of 69% of seismic events occur during the blasting window of 18:00 to 19:00. This allows the rock mass to remobilize and assume its position of equilibrium. It also allows for the safe entry of the following working shift. The remaining 31% of the events occur during the shift. Of concern is that 19% of these events occur when the bulk shift is at work (i.e. 04:00 to 17:00). The goal is to have zero events during the shift. A rating system, comprising of low, medium and high based on the activity rate over a 365-day moving window is used to alert teams of eminent danger and in some cases, prohibit entry into workplaces.

Between 2018 and 2022, events of 0.5ML to 1.0ML, occurring during the shift have been problematic, however recently, events of 1.6ML to 2.5ML are a new challenge in respect of managing seismicity.

3.1 Incident description and seismic analysis

The change in the dip of the reef is an isolated erratic occurrence which is located in a single area on the operation, having a strike length of 400m. Being a rare occurrence, the previous operational decision was to leave this area un-mined. This practice proved successful with minimal risk, however, the strike is variable and tends to meander.

In the early hours of 21 October 2021, a magnitude 2.6 seismic event occurred on the reef horizon in close proximity to the skin of the working place. There was no seismic activity for the 24 hours preceding the major event. When scrutinizing the 6 largest events (Table 1), ML>=0.0, from 1 January 2021, it was noted that the workplace was dormant.



Cluster of events following the large event indicated by the red ball

Moment tensor above indicating a strong element of a slip mechanism

The green line indicates the orientation of the event

Figure 5. Seismic plot of the events and on the right is the seismic analysis.

Table 1. Six largest events since January 2021 in the raise line where the incident occurred.

Date	Time	Magnitude	Date	Time	Magnitude
2021/07/13	20:26:38	0.1	2021/08/18	19:28:53	0.4
2021/08/06	19:19:47	0.1	2021/08/26	16:32:24	1.1
2021/08/08	20:04:35	0.3	2021/10/21	02:08:00	2.5

3.2 Hazard estimation and source mechanism

The statistical seismic hazard estimation is based on the truncated Gutenberg – Richter relationship. Long-term hazard estimation is 1.6, the daily hazard estimation is 3. This is considered low risk.

The mechanism of the event shown in Figure 5, is based on the Seismologist report which indicated that the event had the following source mechanism:

"The estimated source mechanism has an implosive ISO component (39.7%), a CLVD (Compensated linear vector dipole) component that indicates compression along a sub-vertical axis (29.8%), and a DC (Double couple) component that indicates normal slip on a ENE – WSW orientated plane (30.5%)." Reference 1.

3.3 Assessment of the reef position as the face advances from underground observations

When analyzing the geological mappings from February 2020 to 20 October 2021, in relation to the various mining sequences, the following were observed:

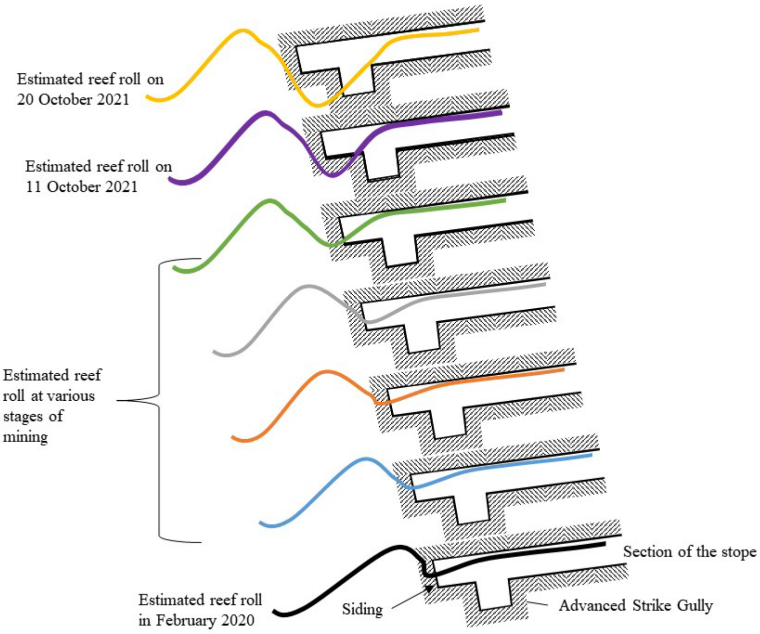


Figure 6. Section view illustrating the projected reef roll positions in relation to the advancing face.

Figure 6 is an illustration of the reef positions in relation to the ASG and siding. When the reef dipped into the footwall this was originally considered as a localized reef roll. The notion of the reef behaving similarly to a fault, was previously never considered. This theory was further tested using numerical modelling.

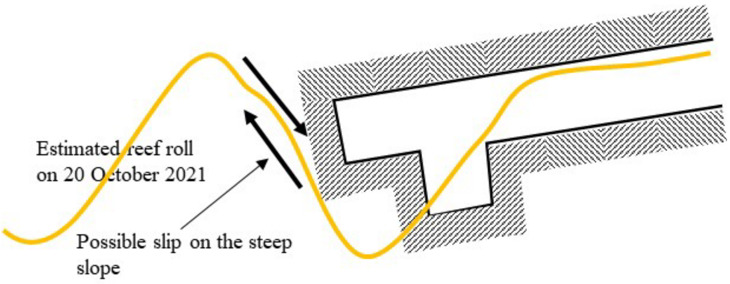


Figure 7. Section view of the stope depicting the slip mechanism.

From the results the calculated ride on the "steep roll structure" parallel to the abutment dipping at about 45^0, Figure 8, where the lobes extend from the abutment into the hanging wall of the panel. The corresponding potency approximates to 50 m^3, being consistent with the DC/shear component of the estimated source mechanism. The associated Excess Shear Stress (ESS) 14-16MPa (Figure 9).

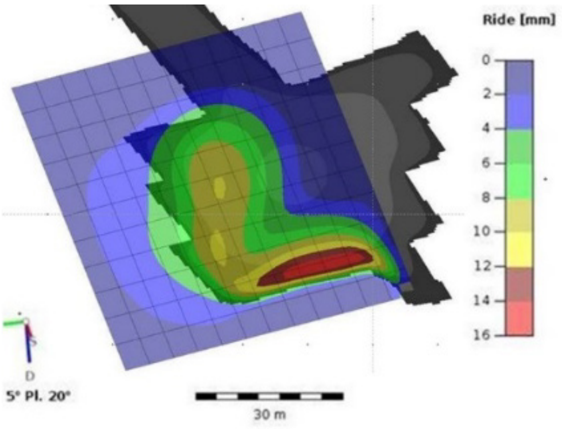


Figure 8. Numerical modeling of ride on the steep reef roll.

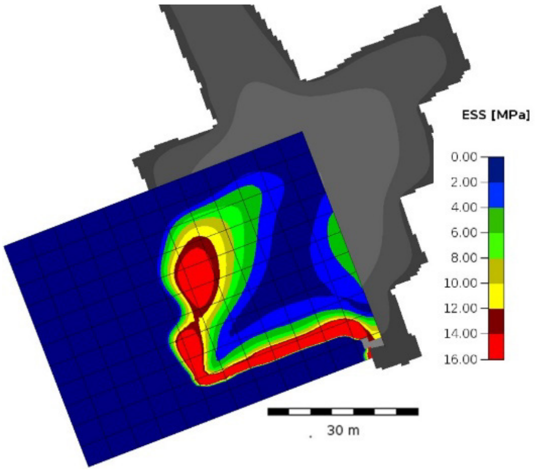


Figure 9. Numerical modelling depicting ESS.

3.4 *Further investigation*

Given this newly acquired knowledge, that the steep reef roll are able to initiate its own slip mechanism, which further correlates with the results from the moment tensor analysis, prompting the scope of the study to be expanded to the adjacent raise lines to justify and confirm this new theory. The raise lines, located 200m to the east and west, were visited to identify similarities. (Figure 10)

- Raise B - Two panels to the east were off reef and in the 3rd panel the steep reef roll was evident. This is consistent with the location, trend and intensity of the seismic events.
- Raise C - The steep reef roll was intersected in the bottom-most panel to the west.

A correlation was drawn between the 3 raise lines and the steep reef roll which could be extrapolated between the raise lines. This was also confirmed during the underground observations.

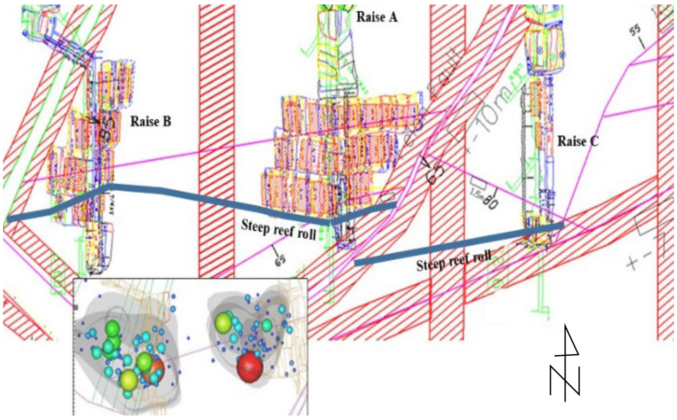


Figure 10. Plan indicating adjacent raise lines and seismic plot insert. Raise A is where the incident occurred.

Events were plotted over time and analyzed, resulting in the nodal planes (from the moment tensor analysis) being aligned to the strike of the reef roll, with a slip type event as estimated source mechanism.

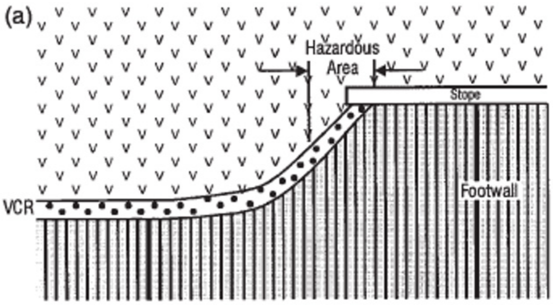


Figure 11. Section view of the steep reef.

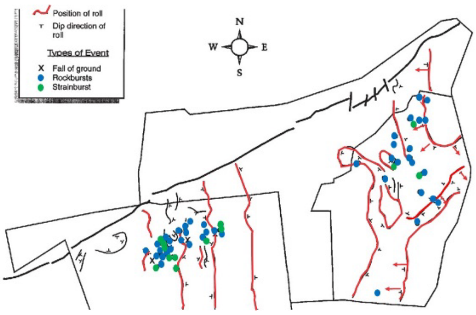


Figure 12. Plan with slopes plotted with the incidents.

This theory was first tested by *Roberts & Schweitzer,* May 1999, where it was identified that on the VCR where the reef goes from a terrace to a slope, an inflection point is created, which proved to be hazardous (Figure 11). Further research by the same literaries revealed that there is a correlation between the location of the slope / terrace and the rock burst related incidents (Figure 12).

4 CONCLUSION

When there is a change in the dip of the orebody when mining the VCR and this deviates steeply (~45^0 or greater from the norm) or where a slope or terrace has been intersected, the potential to generate seismic events is higher. At times these events occur with the blast and are generally missed or ignored. Detailed investigations are conducted only when there has been serious damage or injury. The rationale behind this phenomenon is, at depth, the change in the fracture pattern increases the potential risk of seismicity, mainly due to dynamic brittle shears along pre-existing fractures, in the lava – Ortlepp Shears.

Hanging and footwall rock types, having a high UCS results in squeezing the Ventersdorp Contact Reef, which is much softer, as depicted in Figure 7. Due to volumetric extraction in the adjacent raise lines, this caused loading on surrounding structures. This initiated slip on the structure, thus causing an event of 2.6ML. Following this event the rock mass, in its attempt to assume a state of equilibrium, initiated slip on the steep reef roll, inadvertently causing the abutment sidewall to behave in an explosive violent manner, which also caused ejection of the rock mass.

Roberts & Schweitzer (Figure 11 & 12), pointed this out in an earlier studies, where similar occurrences caused identical consequences.

In addition to the above the adjacent abutment was also assessed and from the assessment it is clear that it did not play a role in the event, as it was of a typical length normally mined on the operation. Although the event plotted close to the abutment; the nodal plane lie parallel with the abutment and the underground observations revealed no indication of abutment failure

Previous learnings from incidents were not disseminated, but captured in mine records or individual papers, however the learnings from this incident have now found their way into design documents and will be shared via various platforms, in order to create awareness.

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