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Mitigating against induced stress from the Merensky Reef pillars on the UG2 Reef mining environment, Tumela 1 Shaft, Anglo American Platinum

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MSc (50/50)	MSc By Research only	PhD
X		

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

20 December 2019

Declaration

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand,
Johannesburg. It has not been submitted before for any degree or examination in any other University.
I declare that I am familiar with the school of Mining Engineering's policy of plagiarism, that the work contained in this research report is my own unaided work, that it is written in my own words, and that all sources of material contained within this report have been suitably acknowledged.

Signed: Carol Leigh Hunter
Date: 20 December 2019

Signature: _____

For my Dad

(1942 - 2018)

Abstract

Tumela 1 Shaft of Amandelbult Section, Anglo American Platinum, is situated south of the town of Thabazimbi in Limpopo Province of South Africa. The Platinum Group Metals (PGMs) are mined from two prominent, narrow tabular, shallow dipping reefs; the Merensky Reef and the Upper Group 2 (UG2) Reef. This mine has experienced an increase in seismic activity from the Merensky Reef stable pillar failures which has increased the risk of mining UG2 Reef close to these potentially unstable pillars. Also, the UG2 Reef areas under Merensky Reef remnants are encountering unusual induced stress effects, which is abnormal for the UG2 Reef shallow depth of mining. The Merensky Reef pillars are in a critical state of stability and stress redistribution by minor UG2 Reef mining can trigger seismic events. In several cases, Merensky Reef seismic events, remote from any UG2 Reef mining, are also triggered. This makes Merensky Reef pillar failures unpredictable. As these seismic events are unpredictable, one must cater for the possibility that seismic shake-down and the effects of induced stress on UG2 Reef can potentially injure people underground. The seismicity and the effects of the induced stress from the Merensky Reef remnants cannot be prevented or predicted - but they can be managed.

To mitigate is to lessen the severity of an occurrence. In the context of mine seismicity, this will involve looking at the entire seismic event: from the source, any triggers, the event properties, and the effect on the UG2 Reef. To be proactive, there is a need to understand what is occurring on the Merensky Reef horizon before mitigation against the stress effect on the UG2 Reef can be done. There is limited information available on this area of research, so the challenge is to ensure sufficient investigations and knowledge transfer to carry forward as the mine progresses.

The focus of this research is to investigate the induced stress from the Merensky Reef pillars on the UG2 Reef mining environment at Tumela 1 Shaft Mine. This is done by two approaches: firstly, underground investigations into whether the Merensky Reef dynamic pillar failures and Merensky Reef remnants affect the UG2 Reef mining as expected; and secondly, to investigate additional strategies to manage the induced stress on UG2 Reef mining whilst maximising extraction. Numerical modelling methods are used, and research suggestions have been applied. Since the seismic monitoring is in place and there are strategies to mitigate against most of the seismic events, the risk still lies with the exposure of mining personnel to potential shake-down and also to the effects of the Merensky Reef stresses on the UG2 Reef. The prediction of seismic events is not possible but a correct, proactive approach can reduce the exposure of individuals to the risks associated with seismic events. Tumela 1 Shaft multi-reef environment is unique, so further mitigation measures against the effects of the induced Merensky Reef stress on the UG2 Reef mining are suggested.

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1. Introduction

1.1. Tumela 1 Shaft geotechnical environment

1.1.1. Locality

Anglo American's Tumela Mine is situated in the Limpopo Province, approximately 30 km south of the mining town of Thabazimbi and forms part of Amandelbult Complex (Figure 1). Mining of the critical zone of the Bushveld Igneous Complex is conducted at this mine. Tumela 1 Shaft is the vertical shaft servicing the down dip areas of Tumela Mine from 8 level to 16 level, approximately 416 m to 946 m below collar elevation.

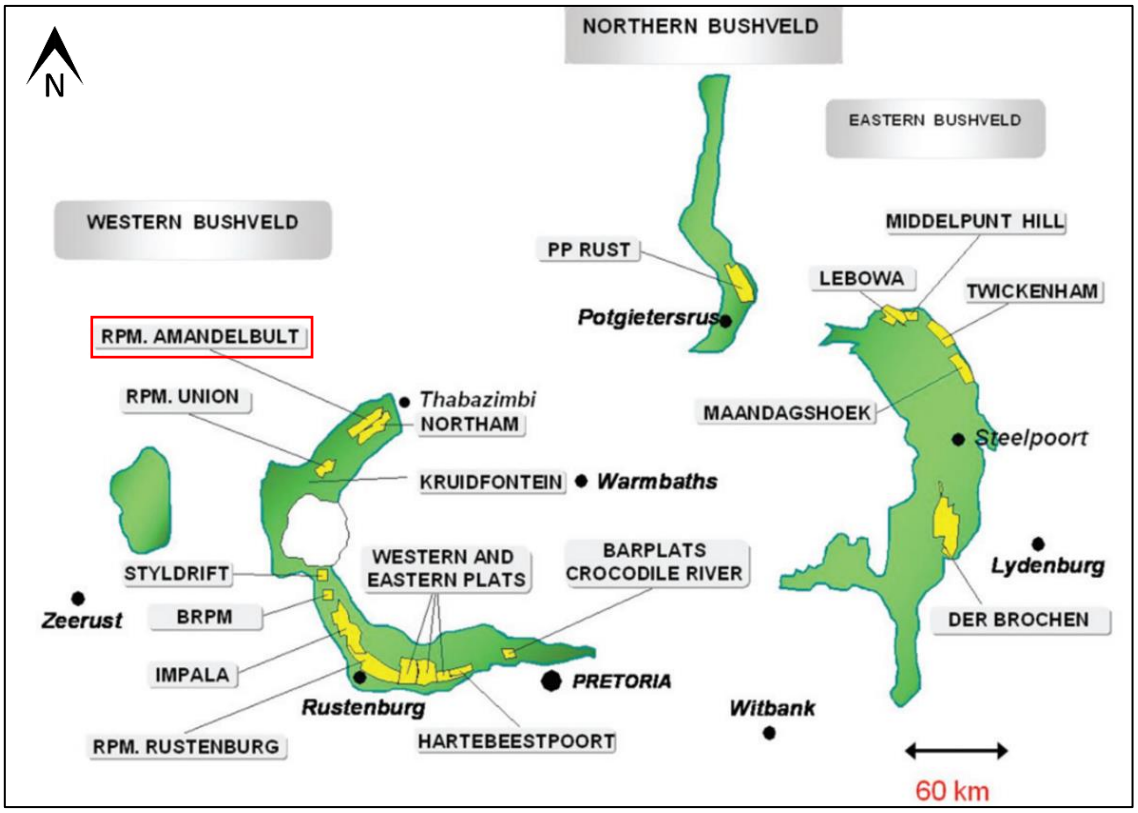


Figure 1: Locality plan showing Amandelbult section within the Bushveld complex (Watson *et al*, 2010 (a))

1.1.2. Stratigraphy

The two main reef bodies of the critical zone are Merensky Reef and Upper Group 2 (UG2) reef, which are narrow, tabular ore bodies dipping south - east at between 18° -23° (Figure 2). The Merensky Reef has been mined extensively, especially on the eastern side of the shaft. The Merensky Reef mining has since been

stopped due to the unexpected intersection of very narrow and uneconomical Merensky Reef “pothole reef” and the economic strengthening of chrome, which is a main constituent of UG2 Reef.

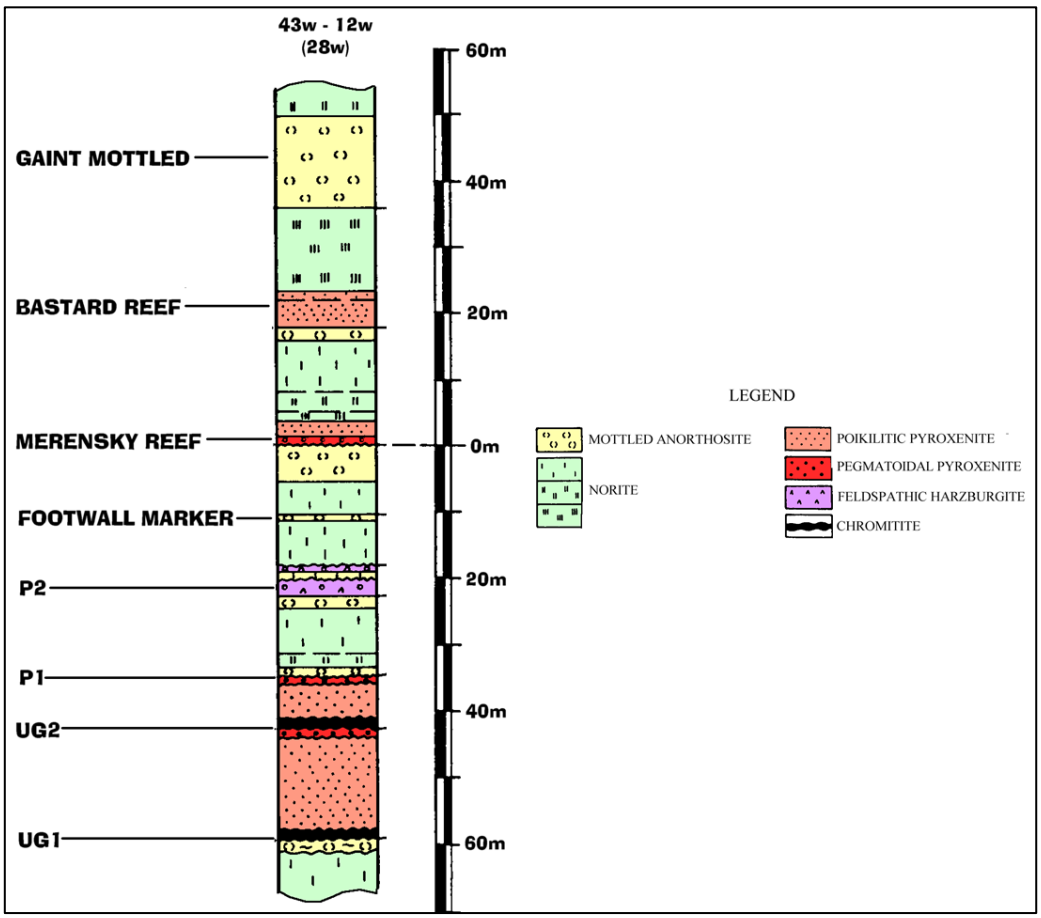


Figure 2: The stratigraphy of the UG2 Reef and Merensky Reef at Tumela 1 Shaft (28W)

The Merensky Reef is located approximately 40 m above the UG2 Reef at Tumela 1 Shaft. This inter - reef distance can vary as much as 30 m due to anomalies such as faults, rolling reef and potholes on both reefs. Stress interactions between the two reefs do occur, especially in the areas below Merensky Reef remnants. This has been observed underground and quantified through stress modelling programs such as IMS Vantage and MAP3D.

The Merensky Reef comprises of pegmatoidal feldspathic pyroxenite and harzburgite with an average uniaxial compressive strength (UCS) of 130 MPa. The reef varies in thickness from zero to approximately 5 m, but averages around 1.2 m at Tumela 1 Shaft, and is terminated by a very prominent chromitite layer, which does not exceed 0.02 m in thickness (Viljoen *et al*, 1986). Above and below the Merensky Reef is a very consistent and strong poikilitic anorthosite. Due to the higher compressive strength of the Merensky Reef, 3.0 m x 3.0 m in-stope pillars were used as stope stability as the Merensky Reef was being extracted.

These are observed on plan to be generally well cut. Merensky Reef mining ceased due to the intersection of pothole reef, which led to the narrowing of the Merensky Reef. Thus, mining became uneconomical.

Prominent contacts between the Merensky Reef and UG2 Reef are the upper and lower pseudoreef (P1 and P2 markers). The P2 marker comprises of two layers and is approximately 25 m above the UG2 Reef. The lower layer of the P2 marker is approximately 3.0 m thick, has a sharp top contact and comprises of a feldspathic harzburgite, troctolite and leuconorite with a thin basal chromitite stringer. The upper layer of the P2 marker is a 0.1 m - 0.15 m zone of coarse pegmatoidal feldspathic harzburgite. The P1 marker occurs approximately 10 m above the UG2 Reef and is a 0.5 m to 1.5 m thick pegmatoidal feldspathic pyroxenite layer. This too has a thin upper chromitite layer (Viljoen *et al*, 1986).

The average thickness of the UG2 Reef chromitite layer is 1.4 m to 1.6 m. The chromitite of the UG2 Reef and the associated leader layers have an average UCS of 70 - 120 MPa (Viljoen *et al*, 1986). A 0.2 m - 0.5 m harzburgite layer overlays the upper leader of the UG2 Reef, which changes to poikilitic pyroxenite. The altered nature of the pyroxenite results in time dependant scaling of the hangingwall and the separation of layers of pyroxenite from the hangingwall. The hangingwall stratigraphy of the UG2 Reef is highly laminated, and with distinct layering and strata separation, which is even more evident in higher stress conditions.

1.1.3. Major geological structures

Water ingress, strata control issues and mining extraction problems are often associated with faults and dykes at Tumela 1 Shaft. During historical Merensky Reef mining adjacent to major geological structures, ground that posed strata control problems was abandoned. This affects the UG2 Reef currently mining as remnant stresses from the overlying Merensky Reef negatively impacts the disturbed ground close to the geological structures.

Three major geological structures are evident at Tumela 1 Shaft (Figure 3):

- The Trainsmash fault system is a 65° dipping, normal throw fault with 10 m - 15 m displacement. This fault is associated with high water flow and strata control issues.
- The Big John dyke is a vertical, 50 m wide dyke with 3.0 m displacement. Seismicity has been experienced from this dyke in the past.
- The Baphlane fault is a 50° - 60° dipping, reverse throw fault. It has displacement of approximately 10 m and is associated with high water flow.

It is observed that panels mined on the weak side of these major structures on both Merensky Reef and UG2 Reef, encounter poor hangingwall conditions which often result in these panels being abandoned. Major faults and dykes are bracketed with protection pillars of between 5 m - 15 m on either side of the

discontinuity at Tumela 1 Shaft. This pillar width is dependant in the fault or dyke properties such as dip and throw of the structure, seismic potential and if the structure is water bearing.

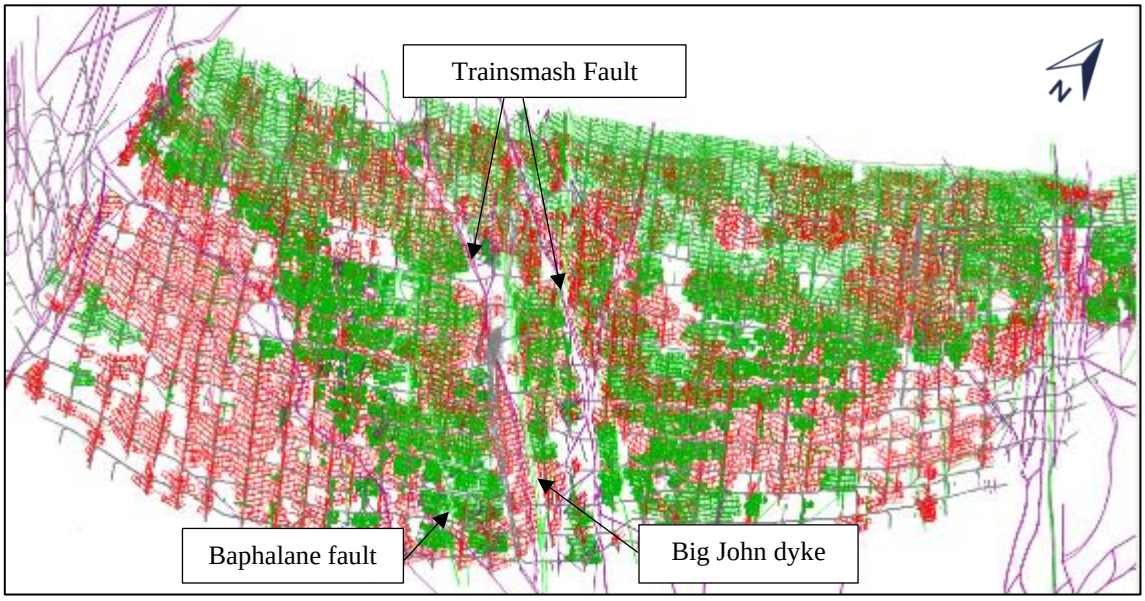


Figure 3: Plan showing the major geological features at Tumela Mine

1.1.4. Tumela 1 Shaft layout and support design

Tumela 1 Shaft layout was not designed to mine UG2 Reef therefore, no special precautions were taken to prevent any issues for a future of multi-reef mining. With the new advances in UG2 Reef refining technology, confidence in deep UG2 Reef mining increasing, and the occurrence of Merensky Reef Pothole reef (resulting in the economic reduction of the Merensky Reef at Tumela Mine), the UG2 Reef became the only way forward to sustain mining. The footwall flat development excavations (haulages, crosscuts) were mined along the P2 marker (Merensky Reef footwall) to accommodate Merensky Reef mining. As the mine is now being mined as a UG2 Reef mine, the flat, mine access development excavations are now in the hangingwall of the UG2 Reef stopes. Ideally, the UG2 Reef development should be in the UG2 Reef footwall to accommodate for correct box tip capacity. This has resulted in the need for many crosscuts to be over-stoped when mining UG2 Reef. In addition, most of the Merensky Reef haulages have 30 m wide protection pillars cut below them on the UG2 Reef plane. Previous numerical modelling has indicated that a vertical distance (middling) of less than 15 m could result in potential collapse of the Merensky Reef haulages into the mined out UG2 Reef panels over time. This would affect tramming of these levels (Bester, 2016). Take - over haulages have been developed deeper into the UG2 Reef footwall to increase the middling between the UG2 Reef, the haulages, and crosscuts. This also results in haulage protection pillars not being required under old Merensky Reef haulages. The development of these take - over haulages are slow; therefore, the haulage protection pillars remain and are incorporated as regional stability.

Regional stability pillars are required to support the entire overburden to surface. Where mining of UG2 Reef in virgin ground is planned, regional pillars are placed on geo-losses or as the final remnant between raiselines. Where UG2 Reef mining takes place after partially extracted Merensky Reef, the regional pillars on the UG2 Reef are vertically superimposed under the Merensky Reef remnants to control induced stress and potential seismicity from these Merensky Reef remnants. These superimposed pillars are designed to have an effective width of 17 m. This was determined from back analysis of a failed UG2 Reef pillar in a high stress stope. This pillar dimension has been successful in the past and confirmed by visits in 2017 to both the Merensky Reef pillar failure areas and the superimposed UG2 Reef pillars directly below (Appendix A).

Tumela 1 Shaft is mined on a scattered breast configuration as Merensky Reef mining was done the same way. Currently only UG2 Reef is being mined at Tumela 1 Shaft. 4.0 m x 4.0 m in-stope pillars are designed as local stope pillar support. Where pre-mining stresses are modelled to exceed 25 MPa (approximately 1/3 of a conservative UG2 Reef UCS), sidings are required to be mined. An underhand mining sequence is used both locally in stopes and per level to ensure that the mining induced stresses are pushed ahead of the UG2 Reef mining front.

1.1.5. Tumela 1 Shaft seismic history and current stress mitigation measures in place

Tumela Mine is considered to be a mine with a low seismic risk when aspects such as risk of injury to personnel, the loss of critical excavations or equipment, and the financial loss due to the failure of a project have been considered (Pretorius, 2005). Although some events are felt on surface they have not generally been associated with damage to underground excavations or surface structures.

With a 40 m middling between the two reefs, this multi-reef environment has many challenges, with seismicity being one. Singh *et al*. (2005) indicated that the ability to mine the UG2 Reef safely in a multi-reef environment relied on, the depth of mining below surface of the UG2 Reef, the distance between the two reefs, and the size of the remnant left behind in the Merensky Reef horizon. Research was conducted at 5-13W UG2 Reef raiseline at Tumela Mine at a depth below surface of approximately 350 m (Urcan *et al*, 2004), but mining is currently at 16 level, which is approximately 950 m below surface.

Visually in Figure 4 and Figure 5, it is clear from the plans that the eastern side of the shaft is more highly extracted on both Merensky Reef and UG2 Reefs. An example is the circled area is Figure 5 which has minimal white areas (unmined ground) compared to the western side of the mine. The western side of the Merensky Reef comprises of more potholes and unmined areas, so the stress concentration on isolated remnants is expected to be lower.

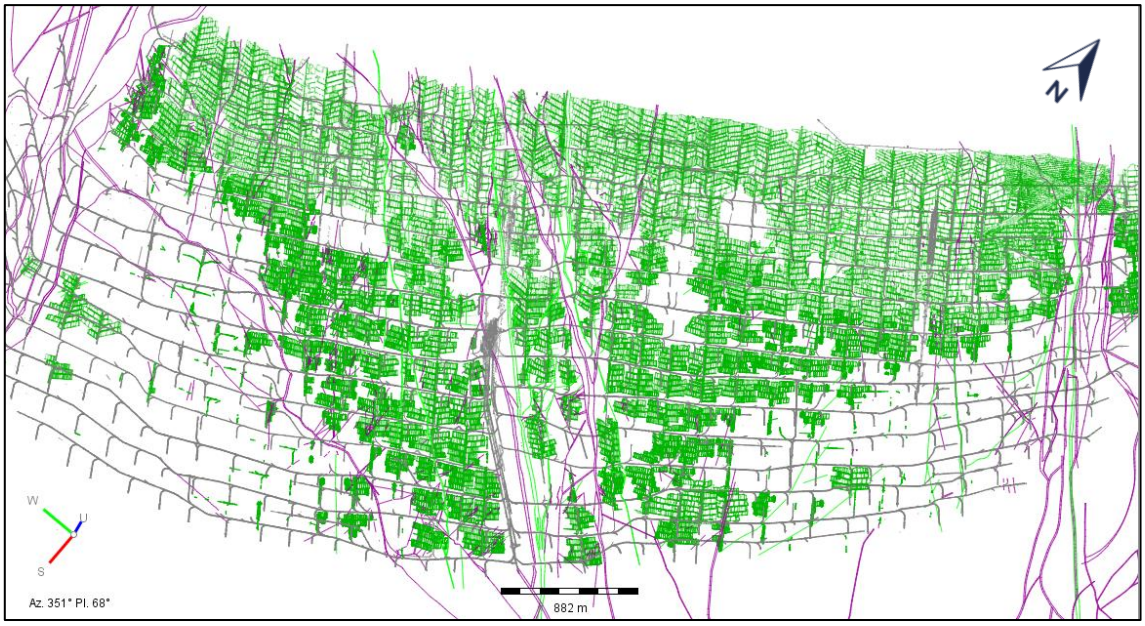


Figure 4: The UG2 Reef extraction at Tumela 1 Shaft

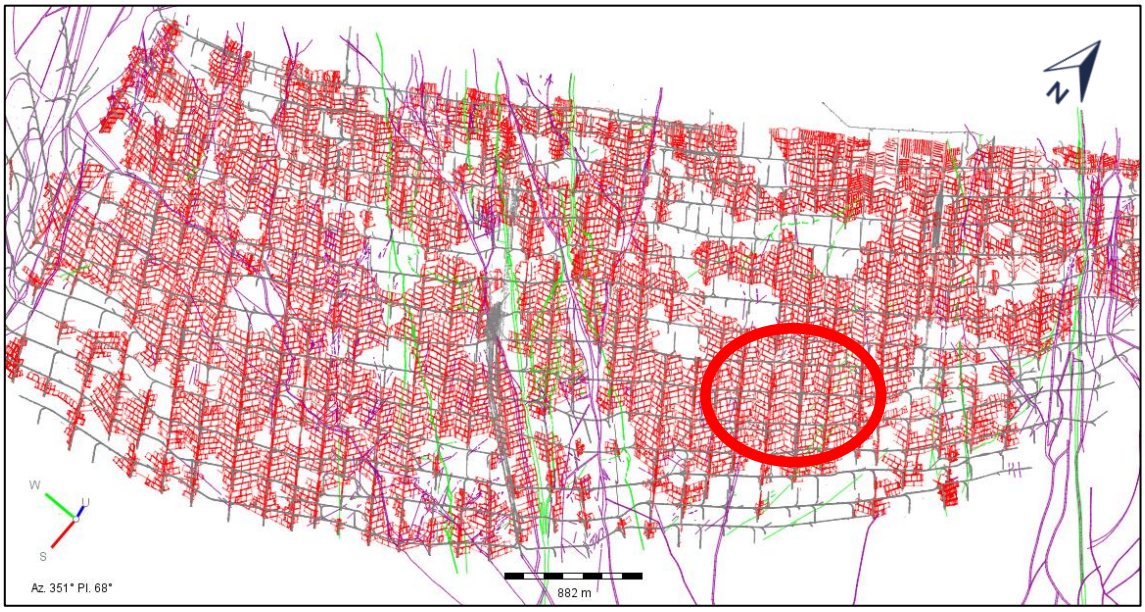


Figure 5: The Merensky Reef extraction at Tumela 1 Shaft. The circled area is where the highest rate of seismicity is occurring at Tumela 1 Shaft. The white areas indicate unmined areas (areas that will still be mined such as potholes)

A flurry of large seismic events recorded during April 2017 in the area between 10 level and 15 level and between the 14W and 20W raiselines (circled area in Figure 6) raised concern about potential damage along the UG2 Reef stopes in this area. No significant UG2 Reef damage was reported from these events. On 2 May 2017, the record-breaking event of Tumela Mine at that time, a M2.6 event, was recorded at the 11-

32W line. This event, and the events of April 2017, prompted the mine to employ the consulting services of the Institute of Mine Seismology (IMS) to determine the causes of these uncharacteristic seismic events at Tumela 1 Shaft. On 17 January 2019, a new Tumela record event of M2.7 was recorded near to 13-18W. No damage was observed in the nearest UG2 Reef panels and only minor shake-down was observed in the haulages.

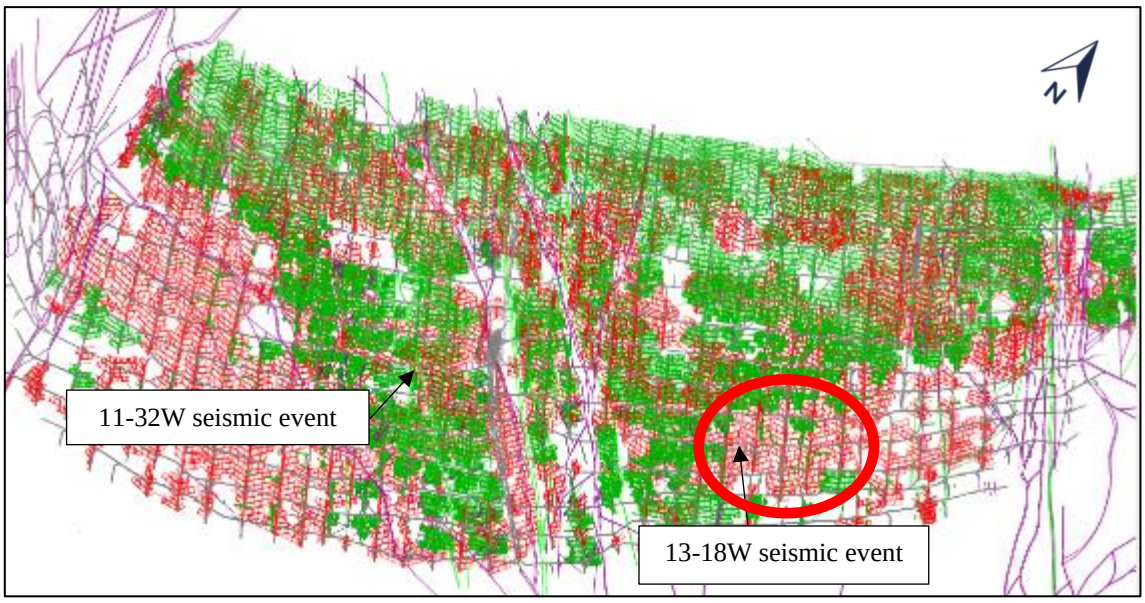


Figure 6: Plan showing the locality of two major seismic events. The circled area is 14W to 20W raiselines where most of the seismicity was occurring

All Tumela 1 Shaft mining is now on UG2 Reef and, due to the softer and weaker nature of the UG2 Reef no violent failures of the designed in-stope pillars are generally expected. There were however recorded UG2 Reef in-stope pillars that failed violently in 2014, two more in 2015 and one in 2016. The exact mechanism is not well understood, but it is believed that strain energy built up over time in these pillars that were cut vertically below Merensky Reef remnants. This prompted the introduction of sidings in UG2 Reef panels that are under the influence of Merensky Reef pillars or remnants, and additional mitigation measures to prevent dynamic failure of oversized UG2 Reef in-stope pillars (such as correct panel sequencing and inelastic stress modelling).

Pillar punching initiates at a w:h ratio of 3 and resistance to punching is reached at a w:h ratio of 10 (Watson *et al*, 2008 and 2010). At a w:h ratio of more than 7, foundation failure, rather than pillar failure, can be expected (Stacey and Page, 1986). Applying these conclusions at Tumela 1 Shaft, stable pillars on the Merensky Reef horizon with dimensions exceeding 10 m are a potential seismic risk at Tumela 1 Shaft. The strategy on UG2 Reef to mitigate against high stress conditions, is to place a pillar with minimum 17 m x 17 m effective width below any Merensky Reef remnants larger than 10 m x 10 m. Also, regional pillars are

placed along the edge of Merensky Reef remnants and spaced a maximum 200 m apart (1/4 depth). Sidings are used in areas which are under a large Merensky Reef remnant, which have not been over-stoped by Merensky Reef, and which exceed a modelled pre-mining stress of 25 MPa. Mining procedures and layouts which replicate those for higher stress, deep mining conditions are in place.

1.2. Project background and introduction to the research

Managing the multi reef mining environment is central to the success of the mining at Tumela 1 Shaft. The placement of UG2 pillars, the practicality of this placement, the support system, and design is dictated by the unmined remnants on the Merensky Reef Horizon. Higher stresses at the edge of Merensky remnants, as well as the pillars left on Merensky, are resulting in seismicity and stress induced issues on the currently mining UG2. There is a need to mitigate against potential seismic risks which can affect the UG2 and the safety of the underground workers. From a Rock Engineering perspective, the need to be proactive (rather than reactive) is vital yet only comes by accurate knowledge and experience of the multi-reef environment underground.

"The vast majority of the mining areas in the Bushveld do not experience seismicity that poses a significant risk to the safety of underground workers" (Brink *et al*, 2002b). The accepted norm is that platinum mines are shallow mines with less brittle rock types than the Witwatersrand goldmines quartzites so there is very little seismic risk. Studies show the seismic risk of underground working on the Bushveld mines is six times less than those in the Ventersdorp Contact Reef (Brink *et al*, 2002b). This may be true in most platinum mines less than one kilometre in depth, yet in a multi reef environment previous studies have found that shallow depth UG2 Reef mining, under the Merensky Reef remnants, can experience stress conditions that are similar to deep and ultra - deep mining conditions (Singh *et al*, 2005). The hazard from seismicity is related to the distance a person is to the source (in the case of pillar bursting) as well as the inability of support to yield whilst maintaining a stable hanging wall in this dynamic environment (Brink *et al*, 2000b).

By visual plan observation, there is a high extraction ratio of the Merensky Reef on the eastern side of Tumela 1 Shaft. As the mining of UG2 proceeds under this mined out reef, the risk of seismicity is assumed to increase due to the interaction between the two reef horizons. It must again be noted that UG2 Reef was not expected to be mined at Tumela 1 Shaft therefore Merensky pillar placement and unmined remnants were considered primarily for one reef mining conditions. Previous investigations on multi reef mining seismic risk at the Amandelbult complex were done in 2002 and 2004 (Brink *et al*, 2002b, Urcan *et al*, 2004). These investigations were done considerably shallower and less extracted areas of the Amandelbult Complex.

1.2.1. The scope of the study and the investigation methodologies used

There are current strategies in place which are applied to mitigate against seismic risk and remnant stresses. However, each underground environment is different with its own set of variables to consider. This report aims to investigate the potential seismic risk, and methodologies to minimise risk, when mining out areas below old Merensky Reef workings at Tumela 1 Shaft. The study was a focussed assessment of the effect of Merensky Reef remnants and induced stresses on UG2 Reef mining. The understanding of rockmass behaviour and induced stresses was done by applying methods and knowledge used in documented research projects, looking at the damage history of underground Merensky pillar failures and suggesting new ways to mitigate the risk.

The first part of this report investigates the historical effects of Merensky Reef dynamic failure on UG2 Reef mining and the anomalous stress effects of Merensky Reef remnants on UG2 Reef mining areas. A literature review was undertaken to understand the current knowledge of multi-reef mining conditions and the applicability of deep mining conditions in a hard rock mining environment to a mine such as Tumela 1 Shaft. Numerous underground visits were conducted to the Merensky Reef dynamically failed pillars and the current UG2 Reef mining directly below these pillars. The observed conditions were analysed using numerical models and compared to the monitored seismicity and layout configurations. Support strategies were also assessed. In addition, the 14-23W UG2 Reef crosscut, which experienced unexpected seismic strainburst, anomalous high closure conditions at 14-20W UG2 panels, and UG2 in-stope pillar failures were investigated to determine the effect of Merensky Reef remnants on UG2 Reef excavations.

The second part of this report investigates minimising risk through the understanding of rockmass behaviour to prevent mining personnel being exposed to the effects of higher induced stresses. Mitigation methods outline improved methods to forecast potential seismic events to lessen the exposure of mining personnel to seismic hazard. It is important to ensure that the appropriate strategies are in place to ensure that the high risk pillars have been properly treated so that the mine personnel on the UG2 Reef horizon are not exposed to potential dynamic pillar failure. The findings were further analysed and changes to existing standards and strategies were suggested. Those suggestions aimed to ensure the protection of mining personnel from potential shake-down and induced stress from the Merensky reef onto the UG2 Reef.

The aim of the research report investigations is to gain appropriate knowledge to prevent exposure of mining personnel to dangerous mining conditions due to the overlying Merensky Reef pillars and to build confidence in the future mine design going forward.

2. The effects of induced stress from the Merensky Reef pillars on the UG2 Reef mining environment

Experience and recorded data over decades in the South African mining industry shows that when mining stops, seismicity slows significantly. In abandoned mines, seismicity increases when the equilibrium is disturbed (such as from flooding) and will stop when a new equilibrium is reached (van Aswegen, 2017). Also, large scale closure is a common observation in areas experiencing higher stresses. These higher stresses may be a result of depth or induced stress from a Merensky Reef remnant. The same phenomenon is seen at Tumela 1 Shaft.

Over a period of approximately two years, a number of observations of the effect of Merensky Reef induced stress on the UG2 Reef were recorded, investigated, back analysed and tracked at Tumela 1 Shaft. These areas are shown in Figure 7 and discussed in the report:

- The "flurries" of high magnitude seismic events from the Merensky Reef horizon and the effect of this on the UG2 Reef mining at 12-21W, 11-32W, and 13-18W;
- The seismic strainburst at 14-23W crosscut protection pillar;
- The anomalous high closure at 14-20W.

Observations of all case studies are summarised in this chapter and details regarding the investigations and analysis can be found in Appendix 1.

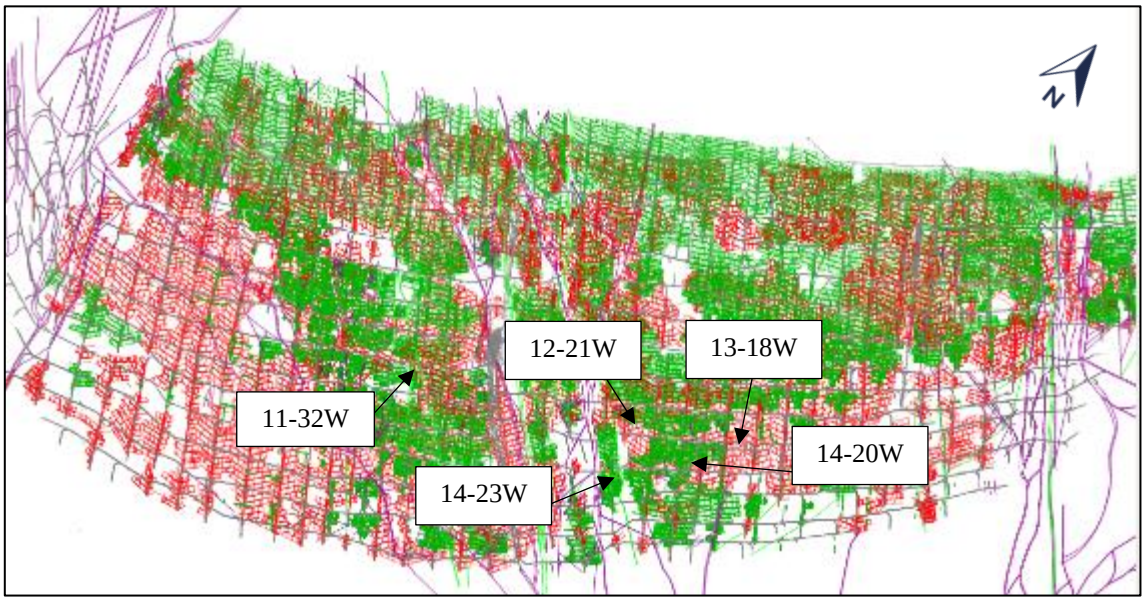


Figure 7: The locations of the research areas

2.1. Literature review

2.1.1. Merensky Reef pillar failure characteristics

There are some similarities between the multi-reef environment and the deep mine environment, such as the high levels of vertical stresses imposed by Merensky Reef pillars on the UG2 Reef. Yet, strong induced tensile stresses, which are not usually encountered in deep mining conditions, contribute to poor the rockmass conditions under a Merensky Reef remnant. This leads to conditions potentially worse than that which is to be expected in a deep mining environment (Singh *et al*, 2005).

Two main types of dynamic rock failure are identified at Tumela 1 Shaft: pillar bursts and strain bursts. On the Merensky Reef horizon, pillar bursts are the most common failure identified. Pillar bursts occur when a pillar of critical dimension becomes over - stressed and fails violently, either failing the pillar totally or partially (Jager and Ryder, 1999). Rock fragments are ejected into the surrounding areas, and dynamic closure is observed in the immediate vicinity (Ortlepp, 1997). In addition, pillar foundation failure is seen in the vicinity of Merensky Reef pillars. This type of failure occurs when the seismic event locates beneath the pillar and is related to Prandtl wedge fractures (Jager and Ryder, 1999; Watson, 2010). The observed damage shows pillar punching into the footwall, footwall heave, stope closure and shake-down damage (Ortlepp, 1997). Strainbursts occur when the stress redistribution causes the strength of rock in the excavation wall to be exceeded, and strain energy stored in the rockmass to be released (Ortlepp, 1997). They are characterized by the violent failure of the intact rock wall of excavations (Jager and Ryder, 1999).

Dynamic pillar failure occurs when the induced stress imposed on the pillars exceeds the peak strength of the pillar, generally in areas where there is a quasi - static stress increase from nearby excavations. The failure is generally not a result of dynamic stress increases from an external seismic source (Kaiser and Cai, 2012). This can be related to the UG2 Reef mining in the vicinity of a highly stressed Merensky Reef pillar and the resulting dynamic failure of the pillar and the pillar footwall at Tumela 1 Shaft. Local mine stiffness plays an integral part in how “violent” the pillar dynamic failure may be. If the local mine stiffness is lower than the pillar, then the failure is violent as more energy is put into the failing pillar than is absorbed by the fracturing process (Maybee, 2000; Watson, 2010). If the local mine stiffness is high in comparison to the post peak stiffness of the pillar, the dynamic failure will not be violent as energy is absorbed by rock fracturing in the pillar. Watson (2010) indicated that in the case of in-stope crush pillars, these pillars should be properly designed to fail close to the face where the loading environment is stiff. However, if these pillars are oversized, these may fail violently, away from the face where the loading conditions are softer.

Another factor to consider is that dynamic pillar failures can occur over time where the principle stress in the rockmass remains constant, but the strength of the rockmass decreases over time. At Tumela 1 Shaft,

the pillars on the Merensky Reef horizon, which are failing, are more than ten years old. The change in stress from the under mining of the UG2 Reef and ahead of the UG2 Reef mining face, causes these pillars to be loaded to levels where they begin to fail. The energy released from a pillar dynamic failure comes from the stored elastic strain energy, which is suddenly released. Pillars can undergo pillar dynamic failures, that completely fail the entire pillar, or they can undergo partial failure that merely eject rock from the highly stressed skin of the pillar while the core of the pillar remains intact (Maybee, 2000). Prandtl wedge fractures may also occur, resulting in foundation failure of the pillar whist the pillar itself remains mostly intact. As the pillar is not completely failed, the core of the pillar is loaded again over time and the process is repeated.

The strength of pillars is controlled by a multitude of factors, which must be considered (York *et al*, 2000). These are:

- Jointing within the pillar.
- Hangingwall and footwall conditions.
- Conditions of the contacts between the footwall/hangingwall and the pillar.
- Dip of the reef plane.
- Total loading system.
- K ratio (virgin horizontal to vertical stress ratio).
- Creep and time dependant deformation.
- Pillar dimensions (inclusive of the pillar width to mining height ratio (w:h)).

Maritz (2015) noted that weak partings are often observed on the interface between the hangingwall and the pillar. Due to the dip of the reef, the shear stress on these partings will cause these partings to mobilise and will possibly cause pillar failures at loads less than expected.

Maybee (2000) and Richardson *et al*, (1999) suggested multiple modes of failure of individual pillars (Figure 8). Structurally controlled failure is controlled by pre - existing failure planes such as geological features (joints, faults). The orientations of these features are unfavourable with respect to the pillar failure and often shear failure occurs along these planes. This is commonly observed on the corners of pillars. A second mode of failure is stress induced progressive failure of pillars. This is where the skin of the pillar, which has little confinement and high tangential stresses, causes cracking and slab formation parallel to the direction of the major principle stress in the pillar. This creates a characteristic hourglass shape of the pillar. Initially the core of the pillar remains intact due to confinement, but as progressive slabbing of the pillar occurs, stress is redistributed to the core, the fractures propagate in the core of the pillar, and thus the pillar loses strength (Maybee, 2000). Also, hangingwall and footwall damage can occur around the pillars, thus increasing the effective height of the pillars. The w:h ratio is generally used as a first indication of pillar strength. A third mode of failure is dynamic pillar failure. This occurs when the stress exceeds the strength

of the pillar and the local mine stiffness must be less than the pillar post failure stiffness. Dynamic pillar failure may involve the entire pillar, or failure may merely eject rock from the highly stressed skin of the pillar while the core of the pillar remains intact (Maybee, 2000).

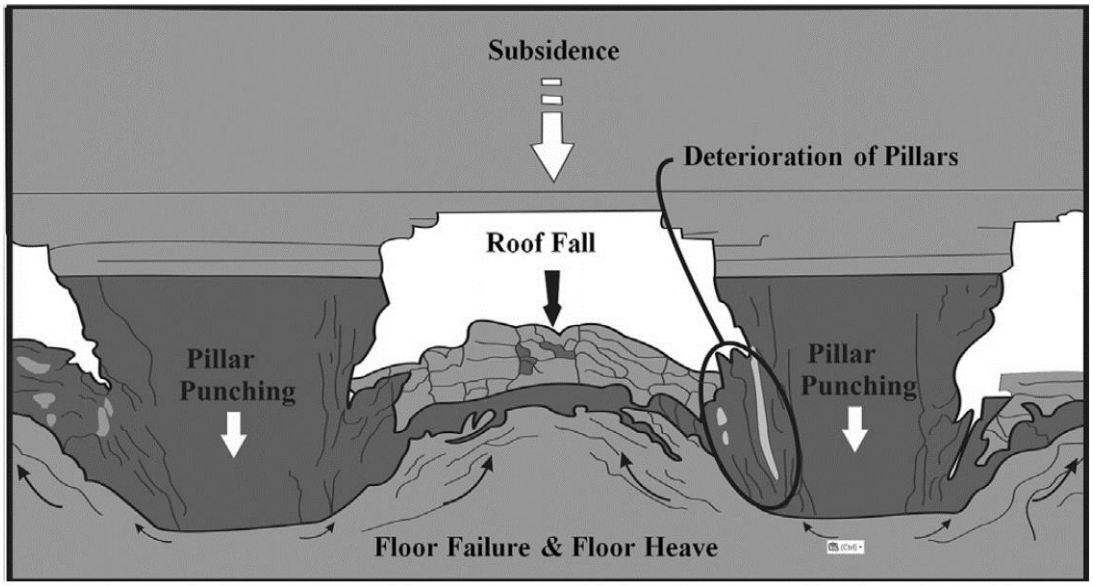


Figure 8: Diagram showing the modes of pillar failure (Richardson *et al*, 1999)

In underground visits to the Merensky Reef horizon at Tumela 1 Shaft (Appendix 1), initial visual inspections can be related to research by de Frey (2002) conducted at the western Deep Levels Mine, which showed that "indestructible pillars", that is pillars with w:h ratio exceeding 20:1, were failing, despite all pillar design criteria being fulfilled. These pillars were designed to avoid any strain softening behaviour within the pillar. However, failure of the foundation of the pillar was not taken into consideration. Research conducted on two geologically different reefs, the VCR and the Carbon Leader Reef in South African goldmines, indicated that foundation failure is inevitable. In addition, back analysis of these pillars showed that the failures were independent of size and depth of mining, which indicated a possible failure in the average pillar stress (APS) calculation for the pillar. The APS was calculated in the design as 2.5 times the UCS of the pillar, but the pillars still failed. This would indicate that there are other failure mechanisms to be considered.

Observations made by Watson (2010) show that hangingwall and footwall failures of pillars occur in several successive stages. Firstly, the fracturing of the pillar occurs where failure of pillars is perpendicular to the sidewall and is the function of applied tangential strain and the confining stress applied to the pillar (Kaiser and Cai, 2012). Secondly, vertical "Herzian" cracks form (after Hertz, 1896) in the foundation of the pillar.

Thirdly, wedges form from shear fracturing and provide the resistance of the footwall to pillar punching. Lastly, pillar footwall punching occurs along "Prandtl" wedge fractures (after Prandtl, 1921), which would ultimately result in inelastic closure of the panel and dilation of the rockmass in the footwall (Figure 9).

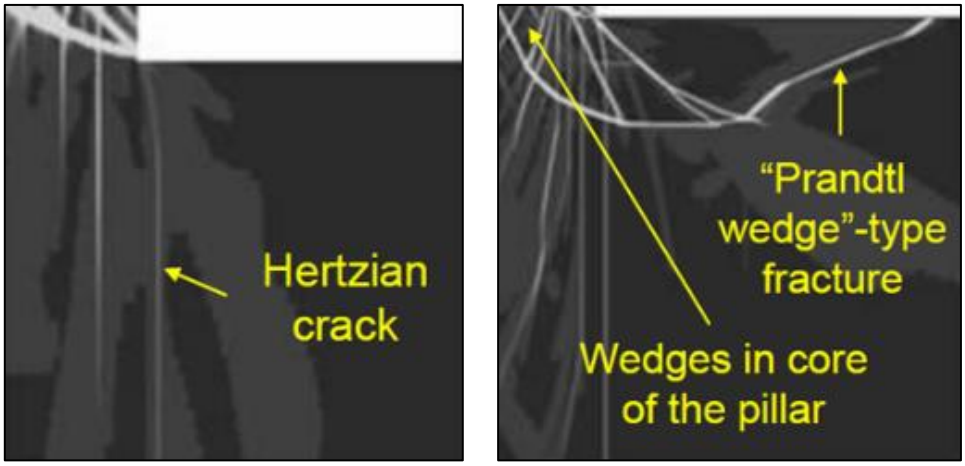


Figure 9: Types of failures in the footwall of a pillar: w:h = 2 (left) and w:h = 5 (right), (Maybee, 2000; Watson, 2008)

Pillar punching initiates above and below pillars with a w:h ratio of approximately 3 (Watson *et al*, 2010). Failure is influenced by the material brittleness of the pillar footwall and little or no damage is likely in the foundations below pillars with low w:h ratios (Watson, 2010).

Numerical models conducted by Watson *et al* (2008), show that the ultimate punch resistance is reached when the w:h ratio approaches 10. He continues to state that "pillars need to be viewed as a system that incorporates the immediate hangingwall and footwall, as well as the pillar itself. With increasing w:h ratio, failure is not contained solely within the pillar, but also expands into the hangingwall and/or footwall. Increasing pillar strength and pillar load results in increasing damage and failure in the hangingwall or footwall". At a w:h ratio of more than 7, foundation failure, rather than pillar failure, can be expected. This is only if the pillar and foundation material are the same (Stacey and Page, 1986). At 11-32W Merensky Reef failed pillar, the w:h ratio of this pillar was 8.6 and experienced foundation failure. This is consistent with the research conducted. At Tumela 1 Shaft, for a w:h ratio of 7 and a stoping width of 1.5 m for the Merensky Reef pillars, the width required for a stable regional pillar is expected to be minimum 10.5 m. Merensky Reef stable pillars with dimensions exceeding 10 m are considered to be a seismic risk at Tumela 1 Shaft.

2.1.2. Expected stress effects of Merensky Reef mining on UG2 Reef

Urcan *et al*. (2004) indicated that UG2 Reef, with higher induced stresses from Merensky Reef mining, may experience:

- Increased face stress, and a potential strainburst.
- Increase in face and hangingwall fractures.
- High energy release rate (ERR) levels.
- Increased seismic risk.
- High closure rate.

The potential failure mechanics of mining UG2 Reef under Merensky Reef remnants is seen by foundation failure of pillars (causing seismic events), and commonly stress fracturing, which may lead to incompetent ground conditions and FOGs. In addition, middling failure may lead to major UG2 Reef back breaks and support with limited yielding capabilities may lead to FOGs. De-stressed UG2 Reef behaves the equivalent to mining panels at shallow depth: low face stress, low seismic risk, reduced fracturing, low ERR. Depending on the size and the middling of the Merensky Reef remnant, and the depth of mining, UG2 Reef can experience conditions similar to deep or ultra - deep mining conditions. Mining conditions are very sensitive to middling (the vertical distance between reefs). A middling less than 40 m or mining reef deeper than 1400 m will experience conditions similar to ultra - deep conditions (Urcan *et al*, 2004).

A seismic strainburst is the interaction of geology, stress, dynamic factors and a variability in materials. Strainbursts are mostly mining induced (Kaiser and Cai, 2013). Progression of sidewall failure is seen to begin with spalling (Villaescusa *et al*, 2016). Spalling begins at a specific ratio of the value of uniaxial compressive strength (UCS or σ_c) to maximum tangential stress (σ_{max}) that is effectively near zero confining stress at the excavation boundary. The value of σ_c/σ_{max} at spalling ranges from 2 to 3.5 for strong to very strong rock (Villaescusa *et al*, 2016). Research has shown that the ratio of uniaxial compressive stress and the induced compressive stress tangential to the wall of an excavation is the primary factor driving the stability of a rock mass. As the ratio of σ_c/σ_{max} reduces, excavation instability increases (Villaescusa *et al*, 2016). A ratio below 5 can show extreme deformation in a low strength rock and sudden, dynamic failure in high strength rock. Back analysis of actual failures in underground mining indicate that the higher the material strength, the higher the measured ejection velocity (Villaescusa *et al*, 2016). This is even more evident in areas of higher stress and as mining becomes deeper.

Figure 10 shows that the stress reduction factor (SRF) of the 14-23W UG2 crosscut at Tumela 1 Shaft is estimated to be approximately 1 and the σ_c/σ_{max} is estimated at approximately 1.6, which would place the excavation in a heavy rockburst zone. At the initiation of slabbing (spalling) as observed in April 2017, the σ_c/σ_{max} was estimated at approximately 3.3.

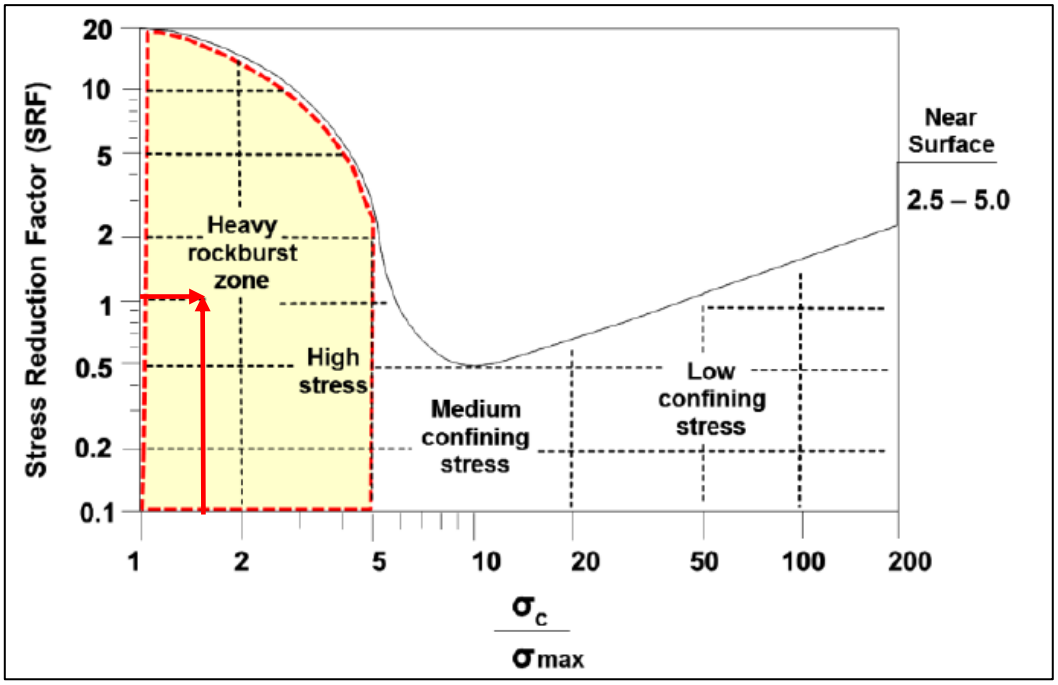


Figure 10: Graph showing the excavation behaviour as a function of compressive stress to the induced stress (Villaescusa *et al*, 2016). The arrows indicate the placement of the 14-23W UG2 crosscut

At the last stages of the spalling mechanism, shear failure on cracks can propagate adjacent to the tunnel leading to a significant reduction in the load bearing capacity of rock. Seismic activity starts with the creation of a vertical tension crack in the hangingwall and footwall of an excavation. The rate of seismicity is seen to increase considerably before overall dynamic failure as the induced stress near the excavation boundary is increased with respect to the intact rock strength (Villaescusa *et al*, 2016). The violent ejection from the excavation walls occur prior to peak intact rock strength.

Two types of seismic damage mechanisms are identified with dynamic failure: near - field damage and shake-down damage. Near - field damage is associated with medium to large seismic events resulting from either the shearing of intact rock, foundation failure or slip on a geological structure (Jager and Ryder, 1999). The damaged areas are affected by the dynamic deformations of rock mass. Shake-down damage is often referred to as “fall of ground associated with a seismic event”. Damage may range from dislodgement of small loose rocks to the fall of large blocks (Jager and Ryder, 1999). This makes the selection of an acceptable support system even more important so that the support unit has sufficient energy absorption and displacement capacity to exceed the energy and displacement demand imposed by a dynamic failure. Load transfer to the reinforcing element of support would stabilise such excavations.

In Figure 11 stress trajectories diagram, as a UG2 Reef panel mines under a previously mined Merensky Reef panel, the UG2 Reef panel under the Merensky Reef is de-stressed. Conditions were similar to that of very shallow mining conditions. As the UG2 Reef panel begins to mine under a Merensky Reef remnant, a high stress concentration will occur at the face of the UG2 Reef panel and exhibit behaviour similar to that of deep mining conditions. The stress change is even more severe as the middling between the reefs becomes smaller.

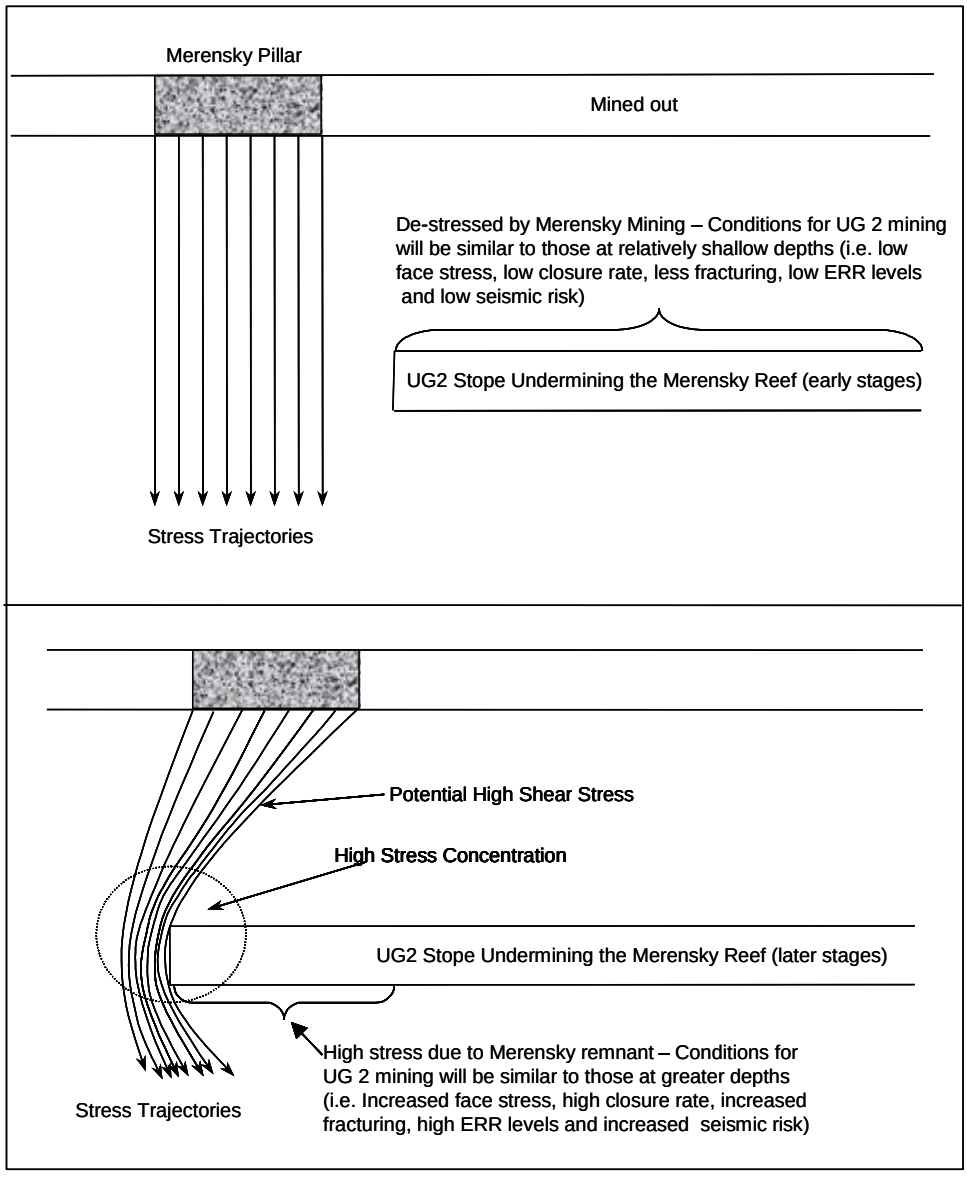


Figure 11: Diagram showing the stress distribution as UG2 Reef mines under a Merensky Reef remnant (Urcan *et al*, 2004)

Closure is the relative movement of the hangingwall and footwall normal to the plane of the excavation; and convergence is the elastic component of closure. Closure is the sum of the convergence and inelastic movements caused by fracturing and the slip and opening of discontinuities such as bedding planes (Malan,

2000). Steady-state closure is the component of time-dependent closure following the primary closure phase after a blast. The rate of steady-state closure gradually decreases when there is no blasting or seismic activity (Drescher and Handley, 2003).

As stated by Drescher and Handley (2003), there are at least four mechanisms responsible for time-dependent hard rock deformation

- Compression creep of the intact rock material.
- Material dilation as a result of stress damage.
- Shear creep on pre - existing discontinuities and stress induced discontinuities in rock.
- Dilation of discontinuities as shear displacements grow with time.

Time dependant deformation encompasses the processes of creep, rate dependent behaviour, delayed fracturing and long-term strength (Malan *et al*, 1997). The time dependant deformation behaviour of rock, that is the elastic and inelastic components of the rockmass movement, is important in dispersing strain energy in rock and thus preventing violent rockbursts (Malan *et al*, 1997). Stiff, brittle rock types, such as those of the Bushveld Igneous complex, will not disperse this energy as rapidly in comparison to the "softer" rock types of coal mines, thus dynamic failure is more evident in hard rock mines (York *et al*, 2000).

2.2. Underground observations and discussions

2.2.1. High magnitude seismic events from the Merensky Reef horizon and the effect of this on the UG2 Reef at 12-21W, 11-32W, and 13-18W

During 2017 and 2018, numerous visits were conducted to large magnitude pillar dynamic failure on Merensky Reef and the UG2 Reef directly below, to observe the effect of dynamic pillar failure of the Merensky Reef on the UG2 horizon, and to ensure that the superimposed UG2 Reef pillars are remaining stable as designed. By plan analysis of both UG2 and Merensky Reef mining, UG2 Reef areas completely overstoped by Merensky Reef mining (11-32W and 12-21W), and Merensky Reef areas not yet understoped by UG2 Reef mining (13-18W) were prioritised (Figure 12).

In April 2017 a flurry of large magnitude seismic events occurred at the eastern side of Tumela mine in the vicinity of the 17W raiseline on Merensky Reef elevation. This triggered much concern, as many events occurred in a short space of time and close to the mining front at that time.
Numerous large seismic events again occurred in December 2017, nearby in location to the April 2017 events. This triggered a visit to 13-18W Merensky Reef panels. This behaviour was different from the usual

seismic events experienced as these very large events occurred as a cluster and is presumed to have been a pillar run. Also, the Merensky Reef stope had not yet been understoped by UG2 Reef in this area.

In addition, in May 2017 an isolated incident occurred on the western side of the shaft. This M2.6 event occurred at 11-32W on Merensky Reef elevation as the rate of extraction of the UG2 Reef increased overall in the mine. On 2 and 3 December 2016, an M1.4 event and a M1.1 event occurred respectively in the vicinity of 12-21W. This area had previously exhibited signs of excessive loading and tensile fractures along the pillar boundaries on the UG2 horizon, which was unusual considering that the area was completely overstoped by Merensky Reef mining. Both the Merensky Reef Horizon and the UG2 Reef panels directly below were visited in 2017. In 2005 to 2008 when only Merensky Reef was mining (UG2 mining had yet to begin), there was an increase in seismicity, but this did not cause alarm. This may be because larger events occurred in the back areas and did not affect the current mining front as the 2017 and 2018 events did (van Aswegen, 2017). Of concern is how and to what extent these large magnitude events potentially affected the UG2 Reef below. Superimposed pillars had been designed directly below potentially active Merensky Reef remnants, but the success of these had never been quantified.

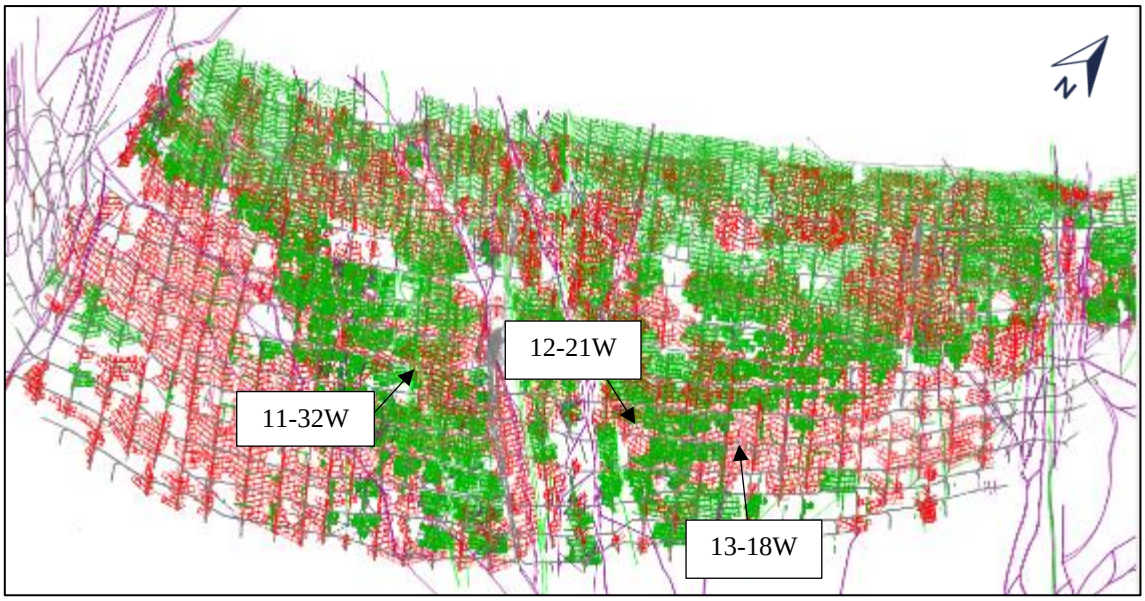


Figure 12: The locations of the research areas

Throughout all visits, conducted to the Merensky Reef horizon and the UG2 Reef directly below, common observations between all sites visited led to a better understanding of the stress environment and the mechanisms which resulted in both the Merensky Reef pillar failures and the induced stress effects on the UG2 Reef horizon.

Common observations made from all sites visited to the Merensky Reef horizon included:

- Merensky Reef in-stope pillars had been reduced to residual strength around large failed Merensky Reef pillars. The in-stope pillar strength reduction had possibly loaded the larger pillar and, as the pillars progressively failed, a soft system was created. This may have contributed to loading the pillar to a critical state before dynamic failure.
- In the observed Merensky Reef pillars, movement was along the top contact of the reef during the dynamic event. This could be seen by pulverised minerals and slickensided planes.
- Hangingwall detachment was observed in all sites visited on the Merensky Reef horizon. This may be time dependant deformation relating to change in rock type in the hangingwall. As the support type used (mine poles) were not designed for dynamic conditions, the overloading of these units had caused them to fail and hence the hangingwall failure.
- Excessive footwall heave was observed around the failed pillar, especially down-dip of the pillar which was consistent with Prandtl wedge failure. The footwall heave was in a confined area around the failed pillar. This confirmed the source of the seismic event was foundation failure of the pillar and the partial failure of the actual pillar as it was pushed into the footwall (Figure 13).
- Comparison with historical data and underground observations showed that Merensky Reef pillars could build up stress for a second time and dynamically fail a second time. A pillar cannot be considered completely failed after a seismic event as the footwall failure may have been the source of the seismic event. The remaining pillar cannot be disregarded in the stress influence from the Merensky Reef to the UG2 Reef. This may be related to different failure mechanisms such as Prandtl wedge fractures causing pillar foundation failure, or by the pillar failure itself.
- Underground observations of all sites showed that at the area of interest on the Merensky Reef horizon, dynamic failure was observed in the pillar, but the pillar had not completely failed as could be seen by a portion of solid pillar on the one side. This may also be related to Prandtl Wedge failures in the footwall.
- Further seismic analysis from Tumela 1 Shaft Merensky Reef failures conducted by van Aswegen (2017) showed that the Merensky Reef pillars were in a critical state of stability and minor UG2 Reef mining (such as developing a raise) could trigger seismic events. These were triggered by the stress redistribution caused by UG2 Reef mining. In several cases, seismic events remote from any UG2 Reef mining were also triggered. This makes Merensky Reef pillar failures unpredictable.
- The mining of the UG2 Reef led to the Merensky Reef pillars to reach the critical state of stress before failure. Once a new flurry of Merensky Reef pillar failures initiated, this contributed to the disturbing effect of these pillar failures that drove further pillar failures. From a stress modelling approach, the Merensky Reef failures were unpredictable (van Aswegen, 2017).

- By plan observation, most of the pillars were uneven in size so the load distribution on these pillars was uneven. Varying rock properties such as joints and faults caused the critical strength of these pillars to be highly variable and made failure difficult to predict (Miovsky and Skeepers, 2007).
- A Merensky Reef pillar failure had a de - stressing effect on underlying UG2 Reef stopes. This was possibly the main reason for the lack of UG2 Reef pillar and hangingwall damage in the UG2 Reef stopes below the seismic events. Stress analysis of this area using IMS Vantage by van Aswegen (2017), showed that a stress reduction of between 1 MPa and 2 MPa were indicated on the UG2 Reef pillar directly below the failed Merensky Reef pillar.



Figure 13: Rotation of footwall slabs due to footwall heave at 11-32W Merensky Reef panel

Common observations were made at the UG2 Reef stopes below and in the vicinity of the Merensky Reef abutments and remnants included:

- The P2 marker potentially functioned as a “buffer” plane between the energy released from the Merensky Reef pillar and the UG2 Reef.
- The superimposed UG2 Reef large stable pillar was not damaged after a large seismic event and high energy release from the failed Merensky Reef pillars and footwall. Only minor shake-down damage and some stress fracturing on the pillar corners were commonly observed (Figure 14). There were no signs of dynamic failure or sudden loading on the pillar. This was consistent for the visits highlighted in this report and also for other post - seismic event investigations conducted on UG2 Reef.

- The failure of the UG2 Reef in-stope pillar was in the actual reef itself and was not dictated by contacts. Hangingwall shears and stress fractures were commonly seen above the failed Merensky Reef pillar whereas in the UG2 Reef pillars this was absent. Minimal footwall heave was also observed around UG2 Reef failed pillars. This finding suggests that the UG2 Reef rock type was similar in strength to the hangingwall rock type (leader seam chromite).
- Any pillar or remnant on the UG2 Reef horizon that was in a critical state (close to failure) could be triggered to fail dynamically by the occurrence of a nearby dynamic Merensky Reef pillar failure (van Aswegen, 2017). Therefore, the UG2 Reef design geometry and good mining practices should aim to minimise the stress on pillars and remnants.
- The UG2 Reef mining front (the advance of all panels and raiselines on all levels) induced stresses on the Merensky Reef ahead. This has shown to trigger dynamic pillar failures within 200 m of this mining front.



Figure 14: The superimposed UG2 Reef pillar corner, at the panel below the 11-32W Merensky Reef dynamic pillar failure, which had little sign of damage

2.2.2. 14-23W crosscut protection pillar dynamic failure

On the UG2 horizon, in the vicinity of 14-23W crosscut, three seismic events (M0.9, M1.0 and M1.3) were recorded on 23 November 2018 (Figure 15). Further investigation showed that the crosscut protection pillar failed dynamically resulting in the above-mentioned seismic events (Figure 16). 15-23W 1W panel was the

only panel blasting at that time and was stopped after the seismic event due to the crosscut dynamic failure and the subsequent risk to mining personnel travelling in this area.

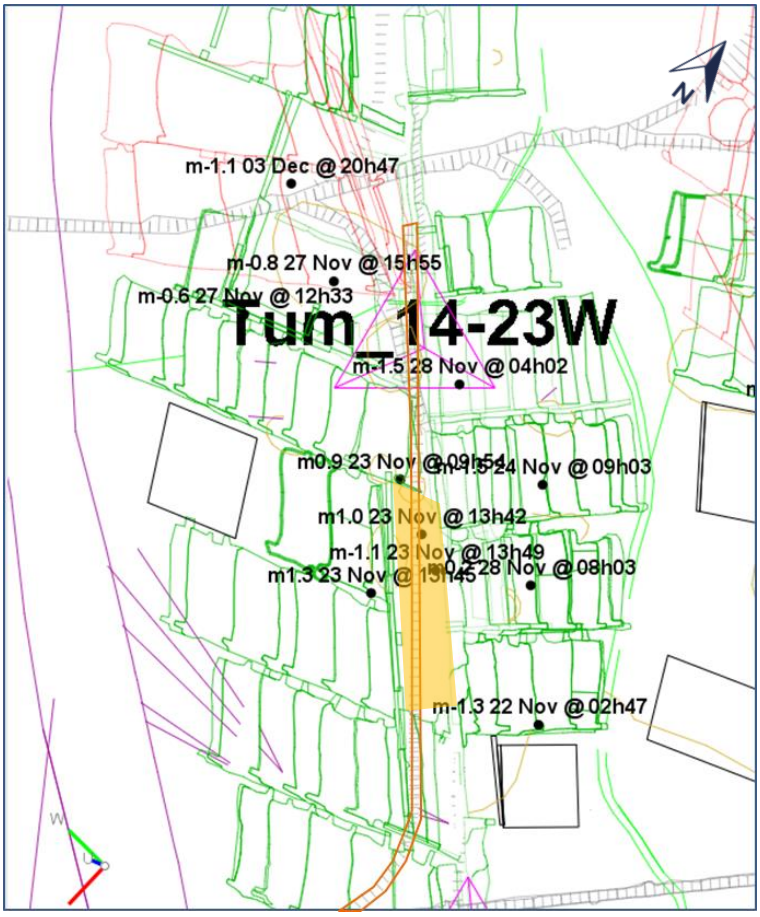


Figure 15: Plot showing all seismic events in the vicinity of 14-23W UG2 crosscut from 20 November 2018 to 31 December 2018. The orange area is the crosscut protection pillar

This event was unexpected as a dynamic failure of a crosscut, such as this one, had never occurred at Tumela Mine previously. Scaling of the crosscut sidewalls was observed from mid-2017, but this was deemed to be manageable with the installation of secondary support and visual monitoring.



Figure 16: Photograph showing the 14-23W crosscut after dynamic failure

At 14-23W, numerous factors coalesced into a scenario which resulted in the crosscut dynamic failure. Underground observations showed possible dynamic failure in the re-raise on the west side of the crosscut pillar and the adjacent areas in the crosscut. Excessive scaling was observed approximately 10 m before the reef intersection (step over position). These higher stress areas observed underground have been replicated in results from the MAP3D numerical model (Figure 17). In this analysis, it is assumed that the rock mass properties are uniformly distributed so that it is possible to use the laboratory results to directly evaluate the in - situ stresses. As the western panels began to mine, stress accumulation was observed at the travelling way position and in the western sidewall. At this time, secondary support was installed. As the western panels progressed, this area of higher stress built up, yet minor change was observed in the stress level as the cubby was mined out (mining step 3). The highest stress changes were observed as the 15-23W 1W panels began to mine (mining step 4 -6). The highest stresses calculated by the model is in the same area of dynamic failure observed in the crosscut and the re-raise underground. In addition, another pocket of high stress is observed from the modelling results where excessive scaling of the crosscut was observed in the week prior to failure (approximately 10 m before the step over position).

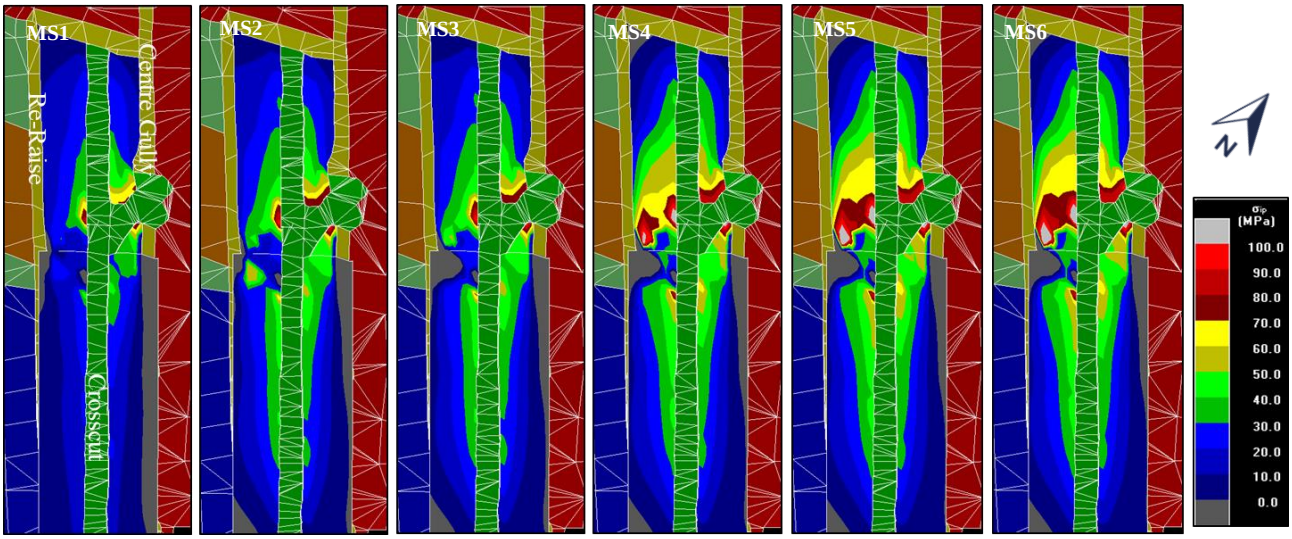


Figure 17: The stress changes (Sigma 1- in plane) made over the six mining steps as shown in MAP3D

A close-up MAP3D analysis over six mining steps was analysed and stress and strain changes were compared. In addition, the model incorporated all possible contributing factors, which may have changed the stress profile of the crosscut leading up to the dynamic failure, namely the winch cubby, the rolling reef (reef undulation) and that the crosscut has mined through the UG2 Reef. The UG2 Reef was modelled as on current layout so model analysis can be compared with underground observations. A number of these factors were confirmed by a sensitivity analysis through numerical modelling (Appendix 1) and a summary is shown in Table 1.

The blasting of the winch cubby was conducted in a breast configuration into the UG2 Reef hangingwall as the reef was undulating (rolling reef). This was at the same elevation as the crosscut. This possibly caused fractures to extend into the crosscut pillar and into the crosscut itself. After the winch cubby was completed, there was only a 2.5 m pillar between the cubby and the crosscut, which was possibly highly fractured. This would have caused a zone of high stress adjacent to this on which dynamic failure could have potentially begun. Stress modelling results showed that there was little stress change and change in stress distribution between the baseline scenarios and if the cubby was not mined out. It can be concluded that the presence of the cubby was a small contributing factor to the dynamic failure of the crosscut.

The crosscut mined through the UG2 Reef and the travelling way was developed perpendicular to the crosscut. The portion of the crosscut, which failed dynamically was below the UG2 Reef and the portion which scaled was above the UG2 Reef. This scenario model did not account for the multiple changes in rock type properties in which the crosscut was mined. Instead, the crosscut was modelled using pyroxenite properties throughout. Results suggested that a rock type change has a significant effect on the stress distribution and the level of stress in the crosscut and the re - raise. The stress decreased significantly from between 70 MPa - 90 MPa to between 50 MPa - 60 MPa once the rock type change aspect was removed.

There is still a slight increase of stress by the mined - out winch cubby, but this is more due to geometry of the winch cubby.

Rolling reef in the panel and western re-raise caused pyroxenite to be exposed in the re - raise. The pyroxenite is a rock of a higher strength, brittleness, and stiffness than the UG2 Reef chromitite. It was observed that pyroxenite had been a possible source of the burst as the pyroxenite on both sides of the crosscut pillar and in similar positions had failed dynamically. The rolling reef (and pyroxenite) present in the re-raise and potentially affecting the crosscut was taken out of the model to test for this scenario. Again, the model did not consider a rock type change from a less stiff UG2 Reef to a stiffer pyroxenite both in the crosscut and the western re-raise. Results show that, when the rolling reef rock type change is removed and the softer UG2 Reef is put in place of the stiffer Pyroxenite, this shows the most significant change in stress distribution and stress amount. The change in stress ranges from between 70 MPa - 90 MPa (Pyroxenite considered) to between 40 MPa - 50 MPa once the rock type change aspect was removed. There is still an increase of stress of up to approximately 100 MPa in the crosscut at the UG2 Reef intersection, but less stress in the re - raise.

An RCF (rockwall condition factor) analysis was conducted on the crosscut. The values of RCF calculated by the model fall within the "average ground conditions ($0.7<RCF<1.4$) range. For areas where there were anticipated stress changes (such as the 14-23W UG2 crosscut), according to Jager and Ryder (1999), primary support would require to be "fully grouted tendons or steel ropes, more than 1.8 m in length, on a basic 2.0 m or 1.5 m pattern" and secondary support would be "medium strength rope lacing and moderate strength wiremesh integrated with primary support tendons". At 14-23W UG2 crosscut, the area of the dynamic failure was supported by 3.0 m long cable anchors, which were pre - stressed to 10 tons, 2.0 m full column grouted tendons and steel "Osro" straps. With reference to the RCF equation, this would be more than sufficient. But there are too many variables to determine whether the support was sufficient as the tectonic stress of the reef roll is not known. The seismic events occurred in the following order: M0.9 at 09:54:31; M1.0 at 13:42:48 and M1.3 at 13:45:56. The M0.9 event did not occur in the crosscut, but instead in the vicinity of the roiling reef on the reef horizon. This may have resulted in the crosscut being dynamically loaded and two events occurring in the crosscut approximately 4 hours later.

The rate of mining may be a factor which contributes to stress being unable to distribute effectively through fracturing and scaling. As determined by the model, an average increase of 30 MPa was induced in the rockmass in this period of time where the mining of 15-23W 1W panel had begun up to failure. This had possibly resulted in dynamic failure of the over - stressed pillar. As highlighted previously, local mine stiffness (or the loading system) is dictated by parameters such as elastic modulus, thickness, and extraction ratio (Kaiser *et al*, 2010). If the local mine stiffness is high in comparison to the post peak stiffness of the pillar, the burst will not be violent as energy is absorbed by rock fracturing in the pillar. When more energy

is put into the failing pillar in comparison with that being absorbed by the fracturing process, excess energy results in violent pillar failure (Maybee, 2000). Due to the rate of mining, the stresses did not have time to be absorbed and redistributed in the fracturing process and thus, the crosscut acted to weaken the pillar and dynamic failure occurred. As the extraction ratio increases to approximately 75% or more, the system became "softer" and the possibility of a violent failure increased (Vardar *et al*, 2017). The 14-23W and 15- 23W panels had an extraction ratio exceeding 80 %.

Figure 18 depicts the panels mining at the time of the 14-23W UG2 crosscut pillar dynamic failure. As indicated by the red star, the 15-23W 1W panel was the panel mining most out of sequence and closest to the shaft. This will indicate that panels this far behind the mining face are under considerably higher stress conditions than the panels mining in the correct sequence. The increase in stress due to depth is directed to the Merensky Reef regional pillars and remnants and this stress is induced onto the UG2 Reef mining. The highest stresses are concentrated at the edges of Merensky Reef remnants and under Merensky Reef regional pillars.

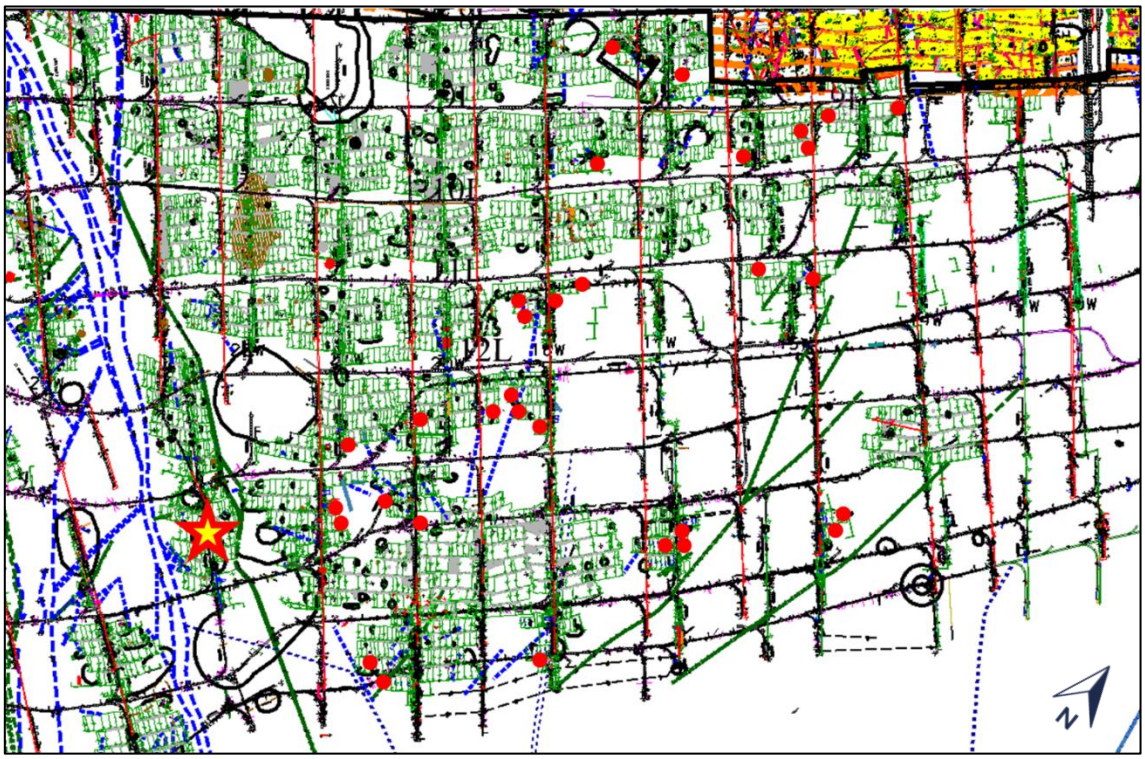


Figure 18: Plan showing 15-23W 1W panel (red star) and the mining panels at the time of the crosscut dynamic failure (red circles)

The sequencing of mining was incorrect and poorly controlled at the 15-23W stope. The panels should have been mined in an underhand configuration with the top panels leading the mining of the bottom panels and with acceptable leads and lags between the panels. Instead the western panels were mined first and the

panels were mined in a sequence from the bottom towards the top. This placed the crosscut pillar under higher than normal stresses as a “remnant” was created and with the accelerated rate of mining of 15-23W 1W, the stresses were unable to redistribute effectively. Non - adherence to common mining “rules” for higher stressed areas such as management of leads and lags and panel mining sequencing, can lead to dynamic pillar failure.

Analysis of all possible influences on the 14-23W UG2 Reef crosscut which may have led to the dynamic failure have been summarised in Table 1:

Table 1: Table showing a summary on the effects of changes to the baseline model on the stresses as observed in the crosscut

Sensitivity and plan analysis	Possible influence causing the crosscut dynamic failure
Winch cubby not blasted and no small pillar between the re-raise and the crosscut created	Minimal
No UG2 Reef/crosscut intersection i.e. no rock type change from UG2 chromitite to pyroxenite, only solid pyroxenite.	Significant
No rolling reef present i.e. no rock type change from UG2 Reef to pyroxenite and back to UG2 Reef.	Significant
Rate of mining of the 15-23W 1W panel.	Moderate
Local mine stiffness influenced from the extraction ratio.	Significant
Mining sequence (regional) i.e. mine was not being mined in a proper underhand configuration and the 14-23W panels were mining a “remnant” of UG2 Reef.	Significant
Mining sequence (local) i.e. the panels in the stope were not mined in the proper underhand configuration and leads and lag distances were not enforced.	Significant
Tectonic stresses from the position of the crosscut between a major dyke and a major fault system	Significant

Non - adherence to proper mine practices in higher stressed areas potentially could have resulted in a loss of life. Identifying high risk areas on the mine is essential in maintaining a safe working environment for underground personnel.

2.2.3. The anomalous high closure at 14-20W

In 14-20W UG2 Reef stopes, higher closure was observed when compared to other panels of similar depths and characteristics. It was observed that the 0.8 m x 0.8 m Cemrite grout packs installed along the centre

gully showed vertical cracks and crushing from unexpected high closure. This was unusual, as the 14-20W panels were not close to being completely mined out. The rate of closure at 14 level was expected to be minimal as there was a reduced span between unmined areas and the area was not deep in comparison to the other higher closure panels (714.7 m below surface).

No prominent geological structures were observed in this centre gully, which eliminated the possibility of an unstable hangingwall block. Instead, as could be seen on plan (Figure 19), the raise on the Merensky Reef had split the remnant over the raise. This smaller portion of the remnant is 44 m long and 30 m wide. Closure was seen where this remnant is, which may have concentrated stress over this area.

Further investigation into the panels showed UG2 dynamic pillar failure at 14-20W 4E panel. This pillar was not oversized and was fully on-reef, thus suggesting that the rate of closure influenced the increased stress in the pillar and did not allow the pillar to release the stress by means of fracturing on the pillar edges. Instead the stress was released dynamically. If the local mine stiffness was high in comparison to the post peak stiffness of the pillar, dynamic failure would not occur as energy was absorbed by rock fracturing in the pillar (Maybee, 2000). This indicates a soft system at Tumela 1 shaft.

IMS Vantage modelling was used to determine the expected convergence profile of the 14-20W raiseline and to compare this to the closure observed/measured underground to investigate if there is an inelastic component of closure in these specific areas. IMS Vantage modelling showed that the area was not expected to be highly stressed. The induced stresses on this area were expected to be 25 MPa - 50 MPa so scaling was expected but not to the extent which was observed underground.

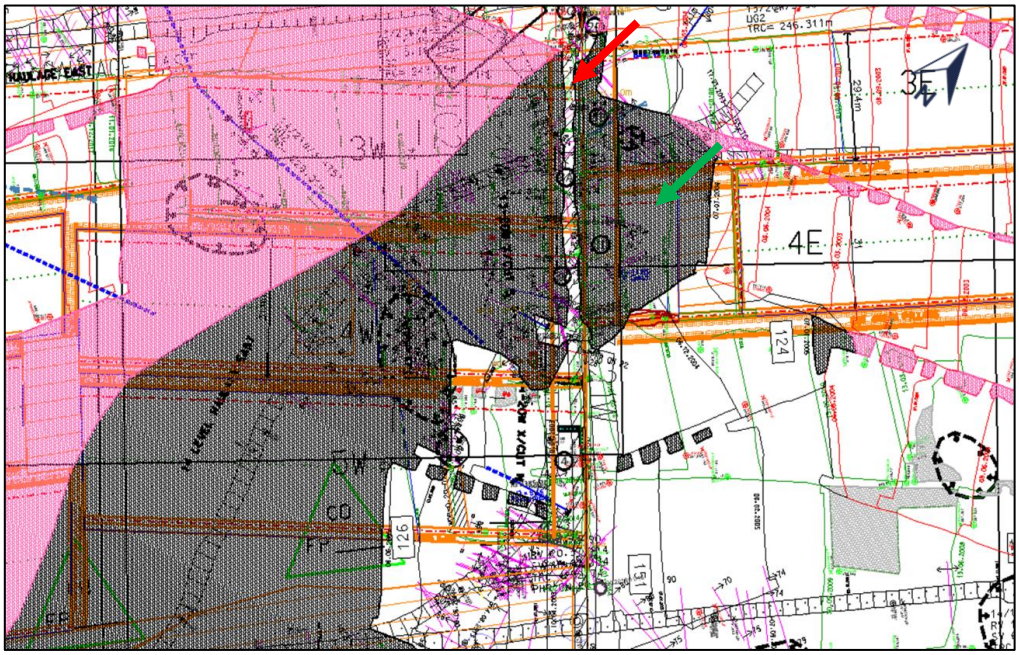


Figure 19: Plan showing the Merensky Reef remnant (black was off - reef and pink was - on reef projections) over UG2 panels. The red arrow indicates the centre gully of 14-20W, and the green arrow indicates the 4E in-stope pillar which dynamically failed

The elastic closure as determined by IMS Vantage modelling (Figure 20) indicates that maximum closure should not be more than 40 mm - 50 mm in the panel and 30 mm - 40 mm over the raiseline. The Cemrite 0.8 m x 0.8 m grout packs maximum deformation at peak load is approximately 61 mm at 2100 kN. The grout packs have crushed considerably to near failure indicating closure of more than 100 mm over the centre gully. This was collaborated by approximate closure measurements from failed timber elongates in the vicinity of these grout packs.

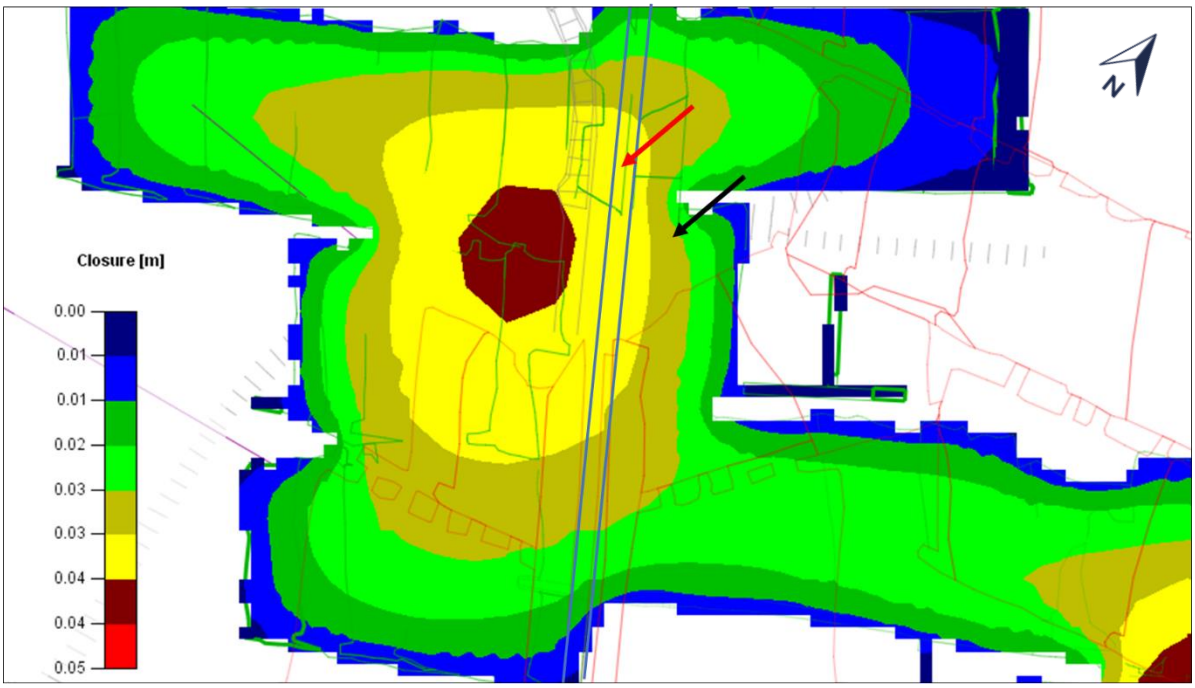


Figure 20: Expected closure at 14-20W panels (current state). The red arrow indicates the centre gully of 14-20W, and the black arrow indicates the 4E in-stope pillar which dynamically failed

Middling between the Merensky Reef and UG2 Reef is approximately 50 m, which is more than the average of the shaft (40 m) so induced stress and closure is expected to be less. The stresses have probably increased even more due to the overall mining sequence being not conducted according to a proper layout for higher stressed areas (underhand configuration or “Christmas tree”). With the larger Merensky Reef pillars at the 17W, 16W, 15W and 14W raiselines having recently failed (as seen by large recorded seismic events), this has potentially put even more stress on this large Merensky Reef remnant area, which may have resulted in higher closure rates.

Underground observations made at 14-20W UG2 centre gully and panels, in comparison with the IMS Vantage stress and closure modelling, indicate there is a significant in - elastic component of closure at 14-20W. 10 m in the hangingwall of the UG2 Reef package is the P1 marker. If this P1 marker is detaching, this would explain the excess loading on the grout packs and the resultant failure of these packs. Further investigation was done to determine if this marker has detached and is excessively loading the 14-20W raiseline.

2.3. Further analysis and discussion

Underground visits show that induced stress from the Merensky Reef onto the UG2 Reef mining can result in:

- Potential detachment of hangingwall strata resulting in excessive closure.
- Oversized UG2 in-stope pillars leading to dynamic failure.
- Shake-down from Merensky Reef seismic events.
- Support failure on the UG2 elevation as current support systems do not cater for potentially dynamic conditions.

Investigations to the Merensky Reef elevation and the below UG2 Reef mining showed there is still a risk for UG2 Reef mining. The Merensky Reef pillar failures and the resulting seismic events cannot be stopped. To keep the mining personnel mining the UG2 Reef safe, proper procedures (such as mining sequences, correct pillar cutting) must be followed.

The second part of this report investigates methods of mitigation and control against the potential effects of stress induced from the Merensky Reef on the UG2 Reef. This section explores effective support measures to ensure safety and for optimisation for UG2 Reef mining.

3. Mitigation against the potential effects of stress induced from the Merensky Reef on the UG2 Reef

To mitigate, by definition, is to lessen the severity of an occurrence. In the context of mine seismicity, this will involve looking at the entire seismic event: from the source, any triggers, the event properties and the effect on the UG2 Reef. Yet, as stated in GAP 608 (Brink *et al*, 2000a) "The researchers found that a coherent data set of seismic early warning case studies does not exist." The research included investigations done at Amandelbult section. At Tumela 1 Shaft, the record seismic event to-date is M2.7 (January 2019). Since the seismic monitoring is in place and there are strategies to mitigate against most of the seismic events, the risk still lies with the exposure of mining personnel to potential shake-down and also to the effects of the Merensky Reef stresses on the UG2 Reef. The prediction of seismic events is not possible but the correct, proactive approach can reduce the exposure of individuals to the resulting risks from seismic events.

As higher stress conditions induced by Merensky Reef remnants on UG2 Reef mining cannot be changed, an integrated approach applying the concepts outlined by Cai (2013) can be beneficial:

- Avoid the hazard. This is done by good mining practices such as layout considerations, maintaining the correct excavation shape and size, and by the correct mining sequence.
- Transfer of energy. This is done by controlled blasting methods such as pre-conditioning and timing of blasts.
- Minimising the risk from rockburst and high stress conditions. This is done by backfill to reduce face stresses, and barriers to keep mining personnel from entering potential rockburst areas.
- Acceptance of the hazard. Having knowledge that an event will potentially occur and to put in mitigation methods, such as effective support systems, to control the rockmass movements and reduce the hazard.

At Tumela 1 Shaft, the use of dynamic support for haulages and crosscuts is a need which has been identified. Proper compliance to procedures by mining personnel, and the reinforcement of these procedures by line supervision, are required to ensure a safe, profitable environment. In a dynamic environment, it is important to ensure that the mine design variables are catered for and all internal hazards are addressed before putting any additional measures such as yielding or confining support systems. The costs involved in more complex support systems can become prohibitive.

3.1. Prediction of seismic events

By definition, prediction means “to make known beforehand”. With reference to seismic events, this would mean knowing the exact place and time of an event or know the mining environment conducive to such events. The prediction of seismicity is controlled by a combination of two factors: the background rate and aftershocks. The background rate is controlled by the mining and geological factors, and the aftershocks are from large events and blasting (Spottiswoode, 2009).

Forecasting is “the estimation of a future event or trend”. An example of this is the probability of an earthquake due to historical information and geological factors. In his analysis, Spottiswoode (2009) analysed seismic data from five different mines with the aim of seeing whether seismicity increased before large events. Small increases were noted, yet the same was noted before small events. The potential for damaging events increased slightly after small events and significantly after large events. Studies conducted by Spottiswoode (2009) that in a 200 m radius around a large seismic event and two weeks before and after a large seismic event showed the following:

- An increased rate in seismicity after the main seismic event.
- Events usually occur after face blasts.
- There is an increased rate of seismicity before and after a seismic event.
- There are more aftershocks after large seismic events.

Furthermore, Durrheim and Ogasawara (2012) conducted their research primarily in gold mines and observed that prior to failure, the density of micro - cracks within rock increases and the mode of deformation changes from linear elastic to non - linear elastic. Durrheim and Ogasawara (2012) suggested that measurable changes can be used to predict the time and location of mining induced parameters, such as stress, strain rate, tilt rate, acoustic emissions rate and micro - crack density. To measure acoustic emissions, a micro - seismic geophone network is required. A normal geophone network measured nine events (aftershocks) of minimum - M0.5 whereas the same area was monitored with an acoustic emissions network and measured 21000 events ranging from - M4.0 to M0.0. In the more sensitive analysis, changes were able to be recorded in detail. This would be a significant tool for current mining conditions but a micro - seismic network would come at immense cost to the mine and to ensure that it is continually reliable, and accuracy would be difficult.

Spottiswood (2009) concluded that short term prediction is not possible. No constant trends were observed to be able to support short term seismic prediction. Forecasting (or estimation) is then used to prepare for events which would possibly affect where mining personnel are working underground. A short - term hazard

assessment strategy would be better employed. As Spottiswoode (2009) suggested, short term prediction cannot be based on seismic rate alone but requires detail. This is limited in sensitivity and resolution of past events and observations.

As the most common mode of failure at Tumela 1 Shaft is pillar burst. This occurs both on the UG2 Reef and Merensky Reef horizons so the loading mechanisms of these pillars are to be considered. From underground visits conducted to the Merensky Reef horizon, there is a possibility of failure of the in-stope pillars around a large stable pillar. These failures may load the stability pillar to a point of failure. In-stope pillars at 13-16W on the Merensky Reef were instrumented, as detailed in the work conducted by Watson *et al*. (2006). In this paper, the average pillar stress (APS) of an in-stope stability pillar increased as the distance from the face increased. This would suggest that around a large Merensky Reef remnant or pillar, in-stope pillars are still highly stressed. These may fail over time and contribute towards excessive stress on the remnant/stability pillar, therefore, potentially over stressing the remnant to a point of failure.

With predictability of a seismic event being one of the difficulty factors when mitigating against these events, Szwedzicki (2003) has looked at various warning signs, which show when a pillar is building up stress and may pose a risk (Figure 21). This is especially useful on the UG2 Reef horizon where pillar bursts are also observed (although not common at Tumela 1 shaft). Szwedzicki (2003) highlighted that there are clear indicators before an event occurs such as the properties of a certain pillar begin to differ from the surrounding rock mass. A geotechnical precursor then warns of the development of high stress conditions or deformations. This is usually detected by instrumentation. The formation of Prandtl wedge fractures increases the potential for the rockmass to fail again. By knowing how the rockmass has failed in the past can provide information into the triggers and the sequence of events in the future.

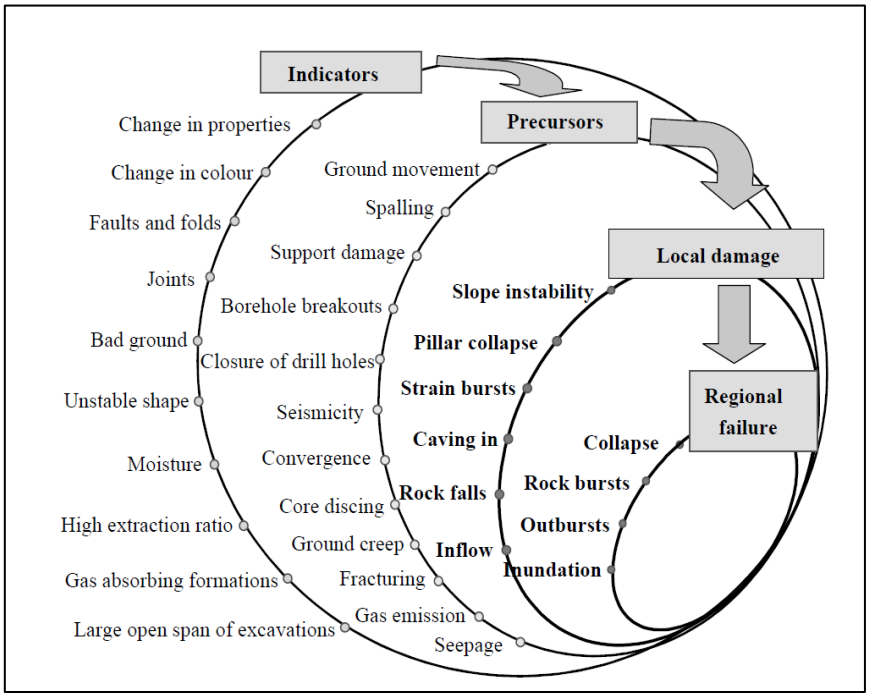


Figure 21: Progression of failure and warning signs (from Szwedzicki, 2003)

3.2. An integrated approach for the management and mitigation of induced stress on the UG2 Reef

High risk conditions are often dealt with in a reactive manner. In platinum mining, FOGs occur by gravitational influence on geological structures in static, lower stress mining conditions. Yet in a multi-reef environment, remnant areas lead to higher than normal closure and stress induced damage on the UG2 Reef. High risk conditions can be associated with this unusual stress and resultant closure. A high risk stope is identified as one where the risk of FOG is higher, and the seismic hazard is higher than a normal stope. Leach *et al*. (2002) stated that 70% - 80% of FOGs occur in high risk areas and usually bound by geological weaknesses. These areas will require specific support considerations.

It is important to note that mining driving forces can be controlled as mining creates a stress field, which may cause seismicity. The concept of prevention - protection - prediction was presented by Riemer and Durrheim (2011). The aim is to reduce seismicity without affecting mining output:

- Prevention employs mining strategies, in which the design and planning of mining layouts are crucial in minimising seismic events. This takes into consideration energy release rate (ERR), excess shear stress (ESS), average pillar stress (APS) and rockwall condition factor (RCF).
- Protection would be to employ specific support systems and strategies to ensure safety of mining personnel and protection of mine openings in a seismically active area.

- Prediction, as described previously, is not possible, so the move to seismic hazard risk assessments and numerical modelling approach is done and is under continuous development.

3.3. Good mining practice for management of higher stress areas

At Tumela Mine, seismically high risk areas have been identified according to underground observations and closure plots from stress modelling. The results have been normalised to ensure it is easy to identify high risk areas. Due to this, criteria which are variable, such as middling distance, is not considered. Elevated stress levels (possible back breaks), changes in rock structure and strength (including elastic deformation) and seismic activity are common factors which occur in these areas. At Tumela 1 Shaft, the following areas are deemed to be high risk for UG2 mining:

- Mining within 15 m of a Merensky Reef remnant larger than 10 m x 10 m in dimension (applying the 45° rule for an average of 30 m reef middling).
- Mining under abutments of larger Merensky Reef remnants where stress concentration will occur.

At Tumela Mine, current seismic risk is managed through the application of good mining practice, which includes rules specifically relating to in-stope pillars and panel stability in high stress conditions. Sidings for areas within a pre-mining stress more than 25 MPa is a strategy which was successfully adopted. These specific areas are determined with IMS Vantage stress modelling. The 25 MPa criteria is determined from the long-term compressive strength of rock which has been found to range between 60% and 80% of the UCS of the rock type. Also, fracture propagation has been shown to initiate at 35% of the peak compressive load (Nyungu, 2013). For Tumela 1 Shaft UG2 Reef, this value is calculated at approximately 25 MPa. A siding will move the stress fracture zone away from the edge of the advance strike gully (ASG) in areas which exceed 25 MPa (Naidoo and Handley, 1998). In areas within a pre-mining field stress in excess of 25 MPa as determined by IMS Vantage modelling, the UG2 Reef in-stope pillars are reduced from 4.0 m x 4.0 m to 3.0 m x 4.0 m with a 1.5 m siding to ensure proper internal pillar fracturing for controlled pillar crushing to reduce bursting potential. Additional findings indicate that leads and lags must be as per the Tumela 1 Shaft design of 4 m - 6 m between panels that are being mined (this excludes panels that are being re - developed). Planning must be conducted to minimise the number of exceptions to this. Straight face shapes must be maintained to avoid irregularities that may become stress concentrators. Triangular shaped pillars or pillars with sharp corners must be avoided. Superimposed pillars are placed where deemed appropriate in accordance to best practice in a multi-reef environment and through analysis of results from numerical modelling programs (IMS Vantage).

3.4. Support systems for a dynamic environment

Due to a high amount of uncertainty and variability in the rockmass properties and stress conditions, all design, layouts, calculations, and monitoring rely on support as the final protection against dynamic failure of excavations. Support caters for the variability and the behaviour uncertainties found within the rockmass (Cai, 2013). An effective support system must have a meaningful design and inputs that can be profitable for a mine with high induced stresses and a seismic rockmass (Kaiser and Cai, 2013). The goal of a support system is for the support to strengthen rock and for rock to ultimately support itself (Hoek and Brown, 1980) by controlling the bulking process and preventing fractures from propagating. The functions of support in dynamic conditions include (Kaiser *et al*, 1996):

- Reinforce the rockmass (strengthen rock and control bulking).
- Retention of rock by preventing keyblock failure and unravelling.
- Holding the rockmass (suspension and reinforcement) to stable elements such as solid rock.
- Integration of support elements to ensure support system integrity.

Yielding support is based on the concept of energy absorption to allow controlled deformation in the rockmass. This has been successful in many mines when compared to conventional static support systems. Conventional support systems on the platinum mines are focused on controlling gravity induced FOGs and stress induced fracturing. In rockburst ground, sudden dynamic loading and rock bulking requires a support system which will yield while containing the rockmass (Cai, 2013). The aim of support in rockburst ground is to meet load, deformation and energy demands of a rockburst environment with appropriate support capacities (Kaiser and Cai, 2013). When energy from a seismic event or from excess induced stress exceeds the capacity of a supported or unsupported rock, failure occurs in the rockmass (Cai, 2013). Rockburst prone ground is usually hard, brittle and fails by extension fracturing, shear fracturing or tensile induced spalling. Fragmentation is usually seen in low confinement areas such as the boundaries of excavations (Kaiser and Cai, 2013). Typical observations seen after a rockburst include rock failure, bulking of sidewalls and of the hangingwall, footwall heave, shearing of rock, falls of ground (FOGs) and rock ejection (rockburst).

A support system is only as strong as its weakest link. If the entire system as a whole is not effective in dynamic conditions, then the entire system fails. Usually the failure of surface retention support (such as mesh or shotcrete) capacity is the weakest link. In higher stress conditions, fractured rock unravels around retaining support therefore areal support is necessary. By holding rock, the energy within the rockmass is dissipated and resulting gravity induced FOGs are prevented (Cai, 2013). Severity of dynamic rock failure is measured by the volume of rock displaced and the depth of failure into the surround excavation (Cai, 2013). The need for an integrated support system, incorporating different support components capable of controlling dynamic conditions, are required (Cai, 2013).

An integrated support system does not need to be complicated - it just requires the features which will achieve the goal of controlled failure in the rockmass. In high stress conditions, the focus is not on preventing the rockmass damage and failure, but rather to control the rockmass failure and prevent it from becoming a hazard (Cai, 2013). It is uneconomical to install excessive amount of support to prevent deformation. The support system must allow yield in a controlled manner. The rockmass will reach a new equilibrium after dynamic loading and deformation and must have the loading capacity to do so.

An effective support system is essential for a mine with high induced stresses and seismic risk. This support system will stabilise an excavation for the life of the excavation (Cai, 2013). The cheaper alternative is static support systems, but consequences and costs involved after a dynamic failure will far exceed that of proper integrated dynamic support systems that are capable of containing rockburst conditions (Moganedi and Stacey, 2019). Consequences of rockburst can be categorised as direct and indirect consequences (Joughin, 2011). Direct consequences are the observed effects in the rockmass; indirect effects are those consequences which have a financial impact. Moganedi and Stacey (2019) further divided the indirect consequences into quantifiable and unquantifiable consequences. By cutting costs on a proper dynamic support system, which does not cater for the conditions of a seismically active and highly stressed mine, the consequences may be (Cai, 2013; Moganedi and Stacey, 2019):

- Damage to the mine openings and access ways.
- Injuries or fatalities to underground workers.
- Rehabilitation costs after uncontrolled failure (re - supporting).
- Loss of production and equipment.
- Poor public image and loss of confidence.

The mine must decide the amount of risk which it was willing to carry without endangering a human life. The acceptance of a level of risk must be informed by the direct and indirect consequences of rockburst and the value that could be created if rockburst was contained with appropriate dynamic rock support (Moganedi and Stacey, 2019). The integrated support is to be cost effective but not with the sacrifice of safety. As the high induced stress risk at Tumela 1 Shaft is variable, the support system caters bother for potential closure by using soft, passive support (grout packs) as well as a static environment by using active support (timber elongates and pre - stressed tendons). In general, a proper cost benefit analysis of the correct support system for each area is essential.

3.5. Treatment of oversized UG2 Reef in-stope pillars

AT Tumela 1 Shaft, seismic risk is known to be a phenomenon applicable to the Merensky Reef but has not been observed on the UG2 Reef. Due to the more ductile nature of the chromitite of the UG2 Reef, no

violent failures of the UG2 Reef in-stope pillars at Tumela 1 Shaft were expected. Some UG2 Reef oversized in-stope pillars failed violently in 2014, and subsequently in 2015 and 2016. The mechanism is deemed to be strain energy built up with UG2 Reef mining oversized in-stope pillars that were cut below Merensky Reef remnants. In order to manage the risk of such a strain energy build up, oversized UG2 pillar strategies at Tumela 1 Shaft are required (in order of application):

1. Risk assessments with remedial measures in the areas where mining personnel are exposed (second escape routes and ASGs).
2. Correct in-stope pillar cutting.
3. Avoid the area of exposure to high stress UG2 Reef pillars by alternative travelling routes.
4. Place barriers in the vicinity of highly stressed pillars.
5. Pre-conditioning of the pillars.

The risk assessment on the areas where mining personnel are exposed, should include the sweepings and vamping activities in back areas and gullies, travelling and escape routes in close proximity of hazardous pillars.

Given that it is impossible for a team underground to know the distance to or magnitude of a seismic event felt in the working place, or the likelihood for further events, the 'if in doubt, stay out' principle must be applied, as a Merensky Reef dynamic failure may trigger dynamic failure on an oversized UG2 Reef pillar. Crews must withdraw if they feel a seismic event underground. Where persons are withdrawn from an area through application of the above principle or through an instruction, re - entry will only be allowed after consideration of the location and size of the event, and subsequent activity. When re - entry takes place, full entry examination must be done. Special attention must be paid to support failure, timber cracking, signs of convergence and loosening of the hangingwall and brows.

Oversized pillars are sometimes created when the ventilation holings are incorrectly mined or not established. Therefore, ventilation holings should be established as per standard specified in the mine stoping procedure. In-stope oversized in-stope pillars must be reduced in size or pre-conditioned while close to the face. This must be conducted before the pillar has reached a maximum distance of 10 m from the face, before the loading system becomes too soft. The decision as to how an oversized pillar should be treated using pre-conditioning must be made in consultation an explosives engineer. A risk assessment must be conducted prior to the commencement of mining the pillar to the correct size, as this might include a change in mining direction and potentially exposing mine personnel to strain bursts. Any drilling into a pillar must be done through a face net and any deteriorating pillar or excessively scaling pillar must be reported to the relevant line supervision.

Second escape routes at the top of panels must not be positioned immediately adjacent to oversized pillars to avoid the area of exposure to high stress UG2 Reef pillars. If there is no alternate route of travel, blasting barricades to be installed adjacent to the highly stressed pillar. Face nets must be used where there is a risk of face bursting.

3.6. Identification of travelling routes that require areal coverage support as a result of predicted vibrations from seismic events

Peak ground velocity, (PGV; also known as PPV, peak particle velocity) is the amount of ground motion produced by a seismic event. This is the "shaking" of the ground, which will potentially cause "shake-down damage" in excavations. The PGV is measured in mm/s. Following a lost time injury that occurred at 11- 14W UG2 travelling way on 20 August 2018, a need was identified to devise a procedure and remedial measures to mitigate the risk of falls of ground caused by "shake-down" of loose rocks from seismic events. The objective was to determine a threshold peak ground velocity (PGV) value and to delineate an area around large, higher risk Merensky Reef pillars (size larger than 10 m minimum width) in which PGVs exceed this threshold value. A radius around potentially seismically active remnants and pillars was determined by literature review and assessing seismic data from previous seismic events at Tumela Mine.

3.6.1. The determination of the appropriate PGV (PPV) and radius

Literature suggests that in a solid excavation, PGVs (PPVs) of 50 mm/s and less are not reported to cause new fractures (MTR Corporation Limited, Hong Kong, 2009; Bureau of Indian Standards, 1973); Persson, 1978; Siskind, 2000). Taking this into account, it was decided that a conservative approach would be to consider a radius around Merensky Reef pillars in which the PGV would be more than 50 mm/s. Only pillars with a diameter of more than 10 m, which were expected to not have previously crushed were included. This was determined from data collected from previous seismic events. For verification of a 50 mm/m PGV, a cumulative graph was created to indicate at which magnitude was at the 95 percentile (Figure 22). The 95-percentile approach was used as this is an accepted way in South Africa platinum mines of quantifying fall of ground data and applying to a support design. The same concept was applied to seismic data. The additional 5 percent required is accounted for by controls such as procedures (seismic response procedure) and support standards. The graph shows that 95% of seismic events (2009 to 2018) are between a magnitude of M0.0 and M1.5.

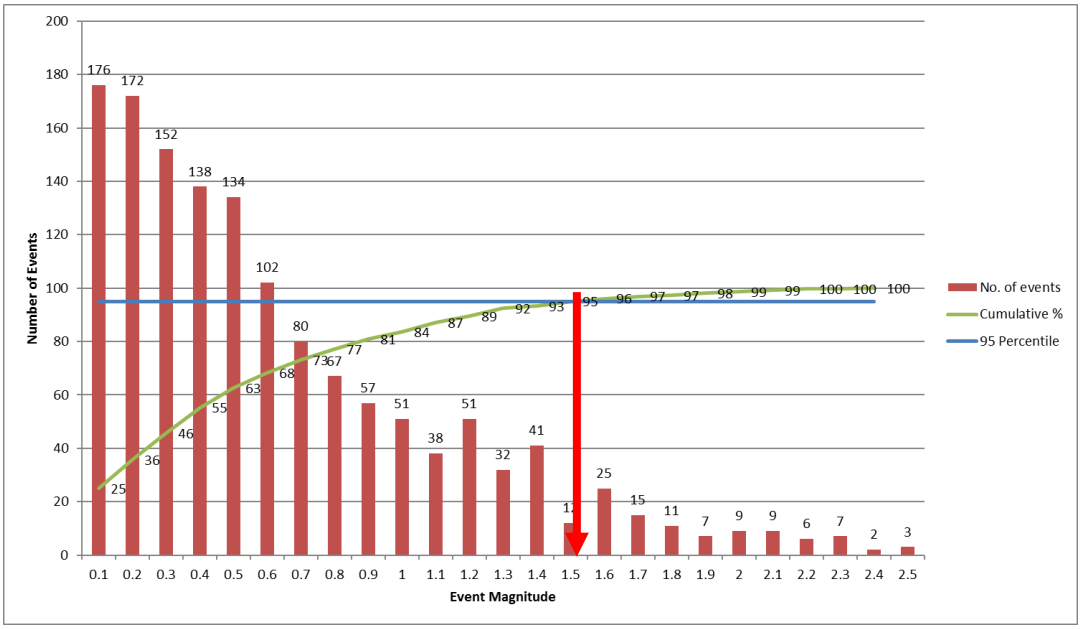


Figure 22: Cumulative assessment of seismic events. Graph shows that 95% of seismic events (2009 to 2018) are below a magnitude of approximately M1.5

IMS was requested to provide PGV data from all M1.6 seismic events at Tumela Mine (2009-2018). This information was represented graphically showing PGV decay over distance (Figure 23). An area close to the source will experience higher PGVs (higher shake-down of loose rock) and then due to PGV decay the areas further away will experience lower PGVs. From Figure 23, a PGV of 50 mm/s from a M1.5 event will affect a radius of approximately 38 m around the source.

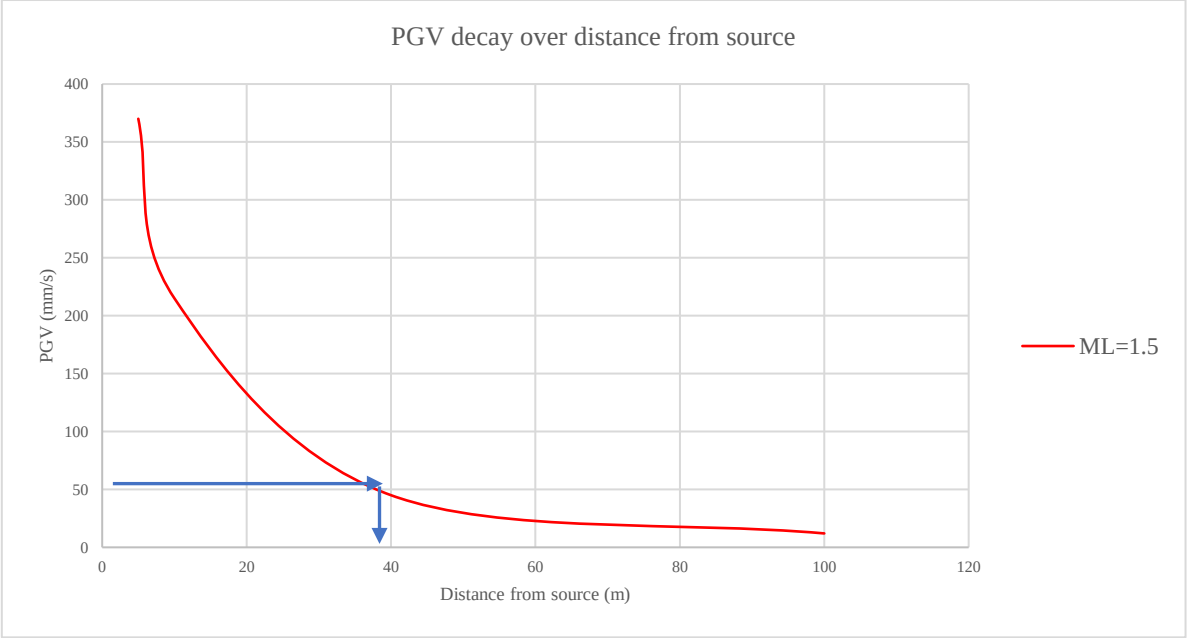


Figure 23: Graph showing the decay in PGV with distance from the source for a M1.5 event

3.6.2. Analysis and Interpretation

Literature and empirical analysis have resulted in the following:

- Empirical data verifies that PGVs of less than 50 mm/s should not cause shake-down if the excavation walls are barred to solid.
- The potential for seismic damage is possible when a seismic event (95 cumulative percentile from Tumela Mine data) is more than M1.5 and PGV is more than 50 mm/s.
- It is expected that a M1.5 event will affect a zone of approximately 40 m around a Merensky Reef pillar with a minimum width of 10 m. Figure 24 illustrates the 40 m radial area that is affected by the critical Merensky Reef pillar.
- Shake-down of loose rocks are still possible in seismic events less than M1.5 and PGV less than 50 mm/s, therefore the inspection of travelling ways as per mine procedure must still be done.

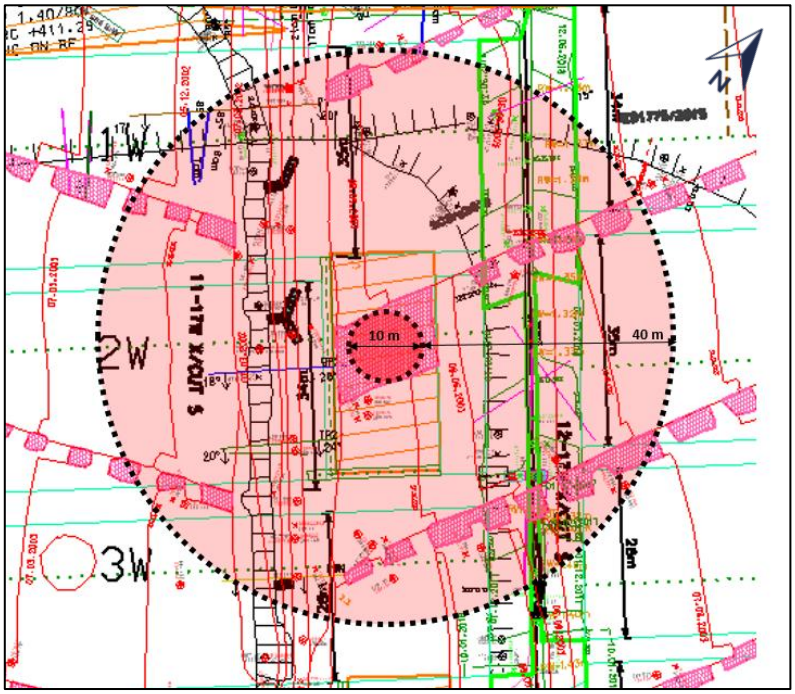


Figure 24: The Figure indicates how to measure the minimum width of a square pillar and the 40 m radial area affected by the Merensky Reef pillar

To confirm the previous assumptions, Figure 25 shows a 40 m radius of a M1.5 event falls within the “fall of loose rock zone” and is unlikely to cause damage to excavations, which have been treated and barred according to procedure.

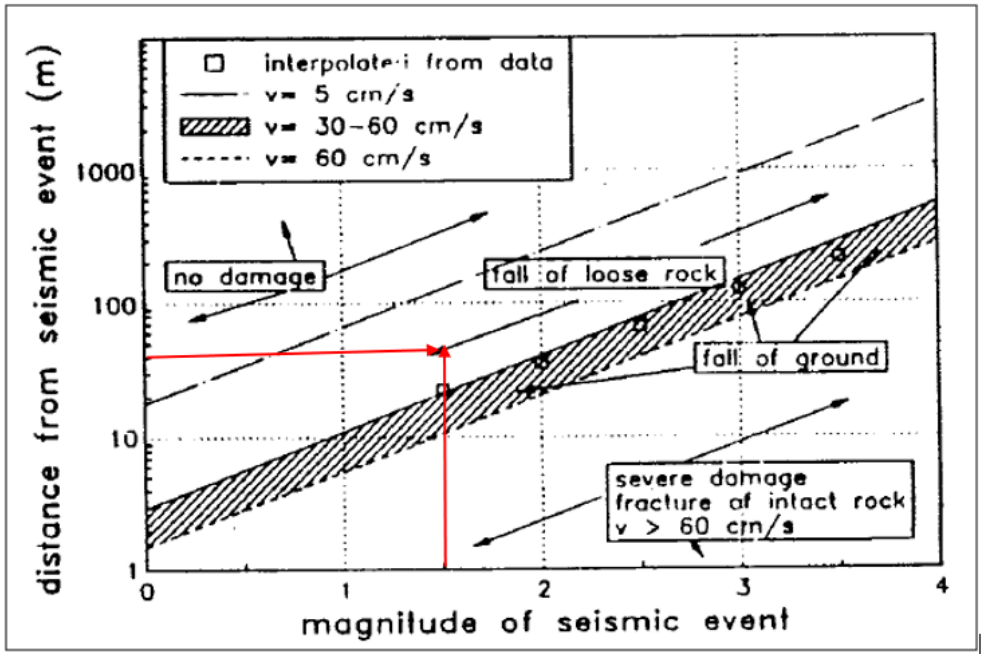


Figure 25: Damage in terms of peak ground velocity (from Lenhardt, 1988). The red arrows indicate the conditions for Tumela 1 Shaft mine for 95% of all seismic events

3.6.3. Remedial actions

A plan of action for workplaces at Tumela 1 Shaft was implemented:

- Each Merensky Reef pillar with minimum width of 10 m to 40 m was identified and a circle with a radius of 40 m drawn around this pillar - the distance was measured from the skin of the pillar/remnant (See Figure 24).
- All travelling ways and step overs in active mining areas under this delineated area without any form of areal coverage support, was covered initially with safety nets in the hangingwall. These nets were attached to the bolts (all attachment points) and tensioned as an immediate measure. For the long term, areal support (mesh) was installed in the identified areas to replace the nets. This areal support provided confinement y*et al*so comprised of a yielding component so that dynamic energy can be absorbed.
- In areas where scraper cleaning was taking place through a travelling way and a temporary safety net was not practical, these areas were prioritised for areal support.
- The FOG risk from shake-down damage when excavations are not barred to solid was communicated to all the underground employees of the mine.
- Abandoned areas and unused areas were barricaded off (as required by the mine's standards and procedures) to ensure no person enters those unexamined areas.

4. Discussion and Conclusion

There is a risk for continued UG2 Reef mining. This has been determined from investigations to the panels where the dynamically failed Merensky Reef pillars are located, and to the UG2 Reef mining directly below. The seismicity from Merensky Reef pillar failures and the induced stress from the Merensky Reef remnants cannot be prevented or predicted. The Merensky Reef pillars are in a critical state of stability and minor UG2 Reef mining can trigger pillar failure and the associated seismic events. These seismic events are triggered by stress redistribution caused by UG2 Reef mining. In several cases, seismic events on Merensky Reef remote from any UG2 Reef mining are also triggered. This makes Merensky Reef pillar failures unpredictable.

It is important to note, that mining driving forces can be controlled as mining creates a stress field, which may cause seismicity. The concept of prevention - protection - prediction (Riemer and Durrheim, 2011) led to an integrated approach to reduce seismicity without affecting mining output:

- Prevention employs mining strategies, in which the design and planning of mining layouts are crucial in preventing seismic events. This takes into consideration energy release rate (ERR), excess shear stress (ESS), average pillar stress (APS) and rockwall condition factor (RCF).
- Protection would be to employ specific support systems and strategies to ensure safety of mining personnel and protection of mine openings in a seismically active area.
- Prediction, as determined previously, is not possible, so the move to seismic hazard risk assessments and numerical modelling approach is done and is under continuous development.

The stress induced from Merensky Reef remnants can have a significant effect on UG2 mining, especially if aspects such as mining sequence are incorrect. The high closure on UG2 Reef results in stresses not being able to be distributed effectively, which can potentially lead to UG2 Reef pillar bursts. The currently installed support is also not designed for this amount of closure. Strategies such as the superimposition of regional pillars on UG2 Reef, adopting deep mining stress procedures and an effective seismic network, to monitor and control Merensky Reef induced stress and seismicity, have been successful. Yet, some unexpected events have occurred, such as the dynamic failure of 4.0 m x 4.0 m UG2 Reef in-stope pillars, abnormal closure and the dynamic failure of the 14-23W UG2 crosscut.

A change in rock type due to mining through rolling reef had a significant effect on the stability and the ultimate dynamic failure of the 14-23W crosscut pillar. The conditions were exasperated by the rate of mining and the poor mining sequence. The crosscut pillar was loaded which resulted in a dynamic failure. At Tumela 1 Shaft, further investigations are being made into the use of dynamic support for larger excavations, such as haulages and crosscuts.

As seismic events are unpredictable, one must cater for the possibility that seismic shake-down and the effects of induced stress can potentially injure a person underground. Support systems, incorporating areal support which is capable of absorbing seismic energy, is identified as a remedial measure to cater for such areas. Using PGV limits to determine a shake down radius is a simple procedure to accommodate for this shake-down yet to entirely cover all areas was very costly for the mine. Instead identification of high risk areas can be done, and these areas treated on a site-specific basis and be risk ranked according to reef middling, vicinity to abutments, and PGV radius.

Underground investigations, numerical modelling analysis and general research have shown that, in addition to induced stress, human mismanagement of stress results in uncontrolled stress effects and dynamic failure occurring in UG2 Reef mining areas and this has financial implications for the mine. Nonadherence to proper mine sequencing, poor mining practice, poor supervision and poor planning have resulted in UG2 Reef excavation failures where they should not have occurred. Measures have been put in place to "design out" the human factor such as installing additional areal support where potential shake-down would occur, instead of barring the areas and doing proper early entry examination, as required. Proper compliance to procedures by mining personnel, and the reinforcement of these procedures by line supervision, is required to ensure a safe, profitable environment. To continue as Tumela 1 Shaft has done in the past will come at a massive cost to the mine and an even bigger incentive to move away from labour intensive conventional mining to mechanised mining methods.

4.1. Recommendations for further research

To ensure the proper support systems are chosen, knowledge of the mining environment needs to be known as seismic events cannot be predicted. This is achieved through historical analysis, experience, field observations and monitoring. There is a need to anticipate issues from high stress conditions but also to be adaptable and change methods according to changing stress conditions encountered. As experienced at Tumela 1 Shaft, conditions in a multi-reef mine can change from replicating a static, shallow mining environment to a dynamic, deep environment in a short time. Seismic information needs to be analysed and compared to the underground situations, so that trends can be identified, and hazard warning plans developed. A more comprehensive model which takes into consideration the stress redistribution within pillars after a seismic event would be ideal.

To accurately design a reliable pillar system, the pillar strength and the pillar load must be known. Additional rockmass data should be collected for the newer areas of Tumela 1 Shaft, which is currently being mined. A large, mine - scale numerical model, which considers bracket pillars, shaft pillars and

haulage pillars is recommended. An in - elastic model should subsequently be run on the pillars to determine the cumulative effect of the pillar spalling and slabbing.

5. Appendix A: Merensky Reef and UG2 Reef case studies

5.1. Merensky Reef and UG2 Reef investigations at 11-32W, 12-21W and 13-18W raiselines

In 2017 and 2018, numerous visits were conducted to large magnitude pillar dynamic failure on Merensky Reef and the UG2 Reef directly below, to observe the effect of dynamic pillar failure of the Merensky Reef on the UG2 horizon, and to ensure that the superimposed UG2 Reef pillars were remaining stable as designed (Figure 26). By plan analysis of both UG2 and Merensky Reef mining, UG2 Reef areas completely overstoped by Merensky Reef mining (11-32W and 12-21W), and Merensky Reef areas not yet understoped by UG2 Reef mining (13-18W) were visited.

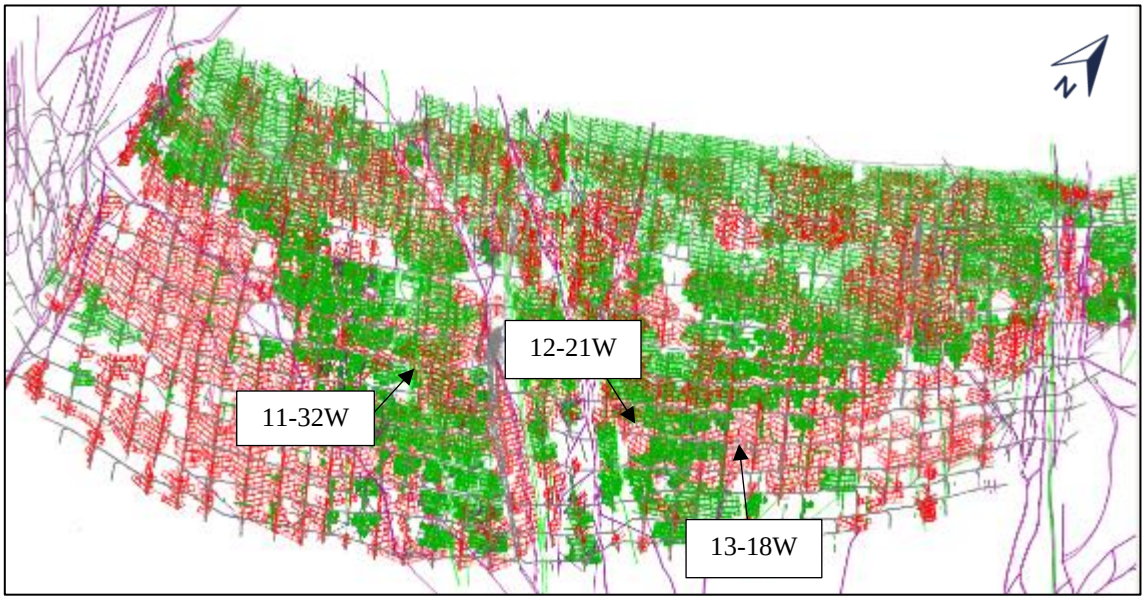


Figure 26: The locations of the research areas

5.1.1. Case Study 1: 11-32W Merensky Reef and UG2 Reef stopes

11-32W was visited after a M2.6 seismic event, which occurred on 2 May 2017 (Figure 27). At the time of the visit this was the largest magnitude event recorded for Tumela Mine. Both Merensky Reef and UG2 Reef had been mined in this area and was approximately 594 m below surface.

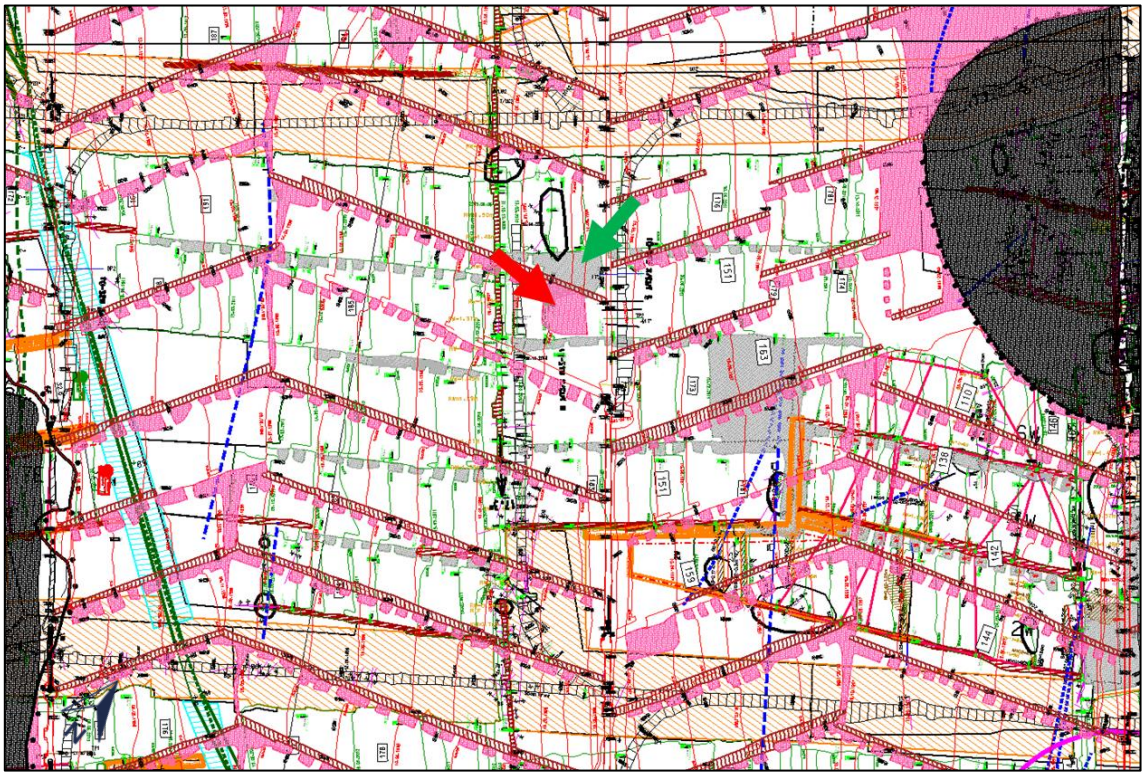


Figure 27: Plan showing the 11-32W UG2 Reef (green) and Merensky Reef stopes (red). The pink hatched areas were the Merensky Reef pillars and the grey hatched areas were the UG2 Reef pillars. The red arrow indicates the pillar which was the source of the event

The Merensky Reef was entered through the 11-32W Merensky Reef crosscut. In this crosscut, shearing was observed along the P2 marker. This identified movement was seen by a 0.02 m - 0.05 m seam of gouge. This was fresh shearing as it was observed over the entire exposed length of the marker which was previously covered with whitewash. Shake-down of loose rocks was observed from the sidewalls and the hangingwall of the crosscut.

The area of interest, the Merensky Reef failed pillar, was approached, firstly, up the centre gully and then the failed pillar was approached from the up-dip side. Observations made in the Merensky Reef stopes showed that the 16 m x 18 m failed pillar was approximately 7 m from the centre gully so there was considerable damage observed in the centre gully from this seismic event. Tensile cracks were observed in the centre gully hangingwall and extensive shake-down damage was observed.

The RSS grout packs (steel ring grout packs) adjacent to the centre gully had experienced very high vertical closure and loading as shown by the vertical cracks in the grout packs. Some grout packs also exhibited hourglass shape failure (Figure 28). A double line of grout packs had been installed along the shoulders of the centre gully and both lines had failed, and complete disintegration of grout packs was observed close to the failed pillar.

Up-dip of the suspected failed Merensky Reef pillar, 0.4 m of hangingwall detachment was observed (Figure 29). This was in one solid beam. The hangingwall overall was minimally jointed and very competent in the surrounding area. No change in rock type was observed and this was confirmed by plan observations of previously recorded geological structures.



Figure 28: Grout pack failure showing excessive closure. These grout packs were adjacent to the centre gully. This pack was originally 1.0 m in diameter

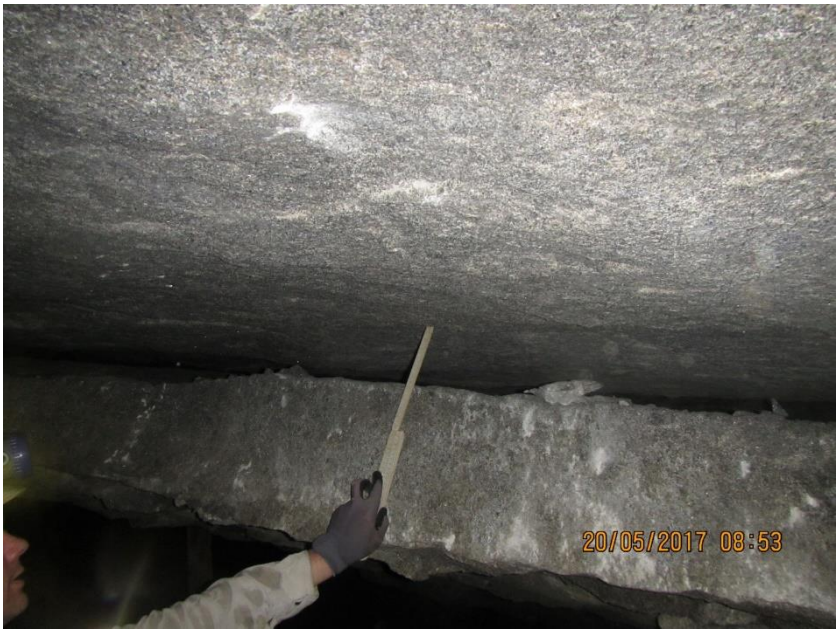


Figure 29: Hangingwall detachment in the vicinity of the failed pillar

The failed pillar's top contact was pulverised reef material of approximately 0.02 m. Slickensides were seen on the top contact indicating that the pillar sheared along this contact in the dynamic failure, which would explain the minimally affected hangingwall. The energy, which was transferred though the reef material, disintegrated the pillar structure into sand. The pillar decreased in size by approximately 0.8 m due pillar disintegration (Figure 30 and 31). This pillar may had been wider before stressed induced fracturing began.



Figure 30: The failed Merensky Reef pillar. Movement along a contact plane between the pillar and the hangingwall



Figure 31: The failed Merensky Reef pillar showing the high energy release to completely disintegrate the structure of rock

Excessive footwall heave was observed around the failed pillar, especially down-dip of the pillar which was consistent with Prandtl wedge failure. Distinct fractures could be seen in the footwall near the pillar. Completely failed timber elongates were observed in this area. The footwall heave was in a confined area around the failed pillar with a radius of approximately 10 m. This confirmed foundation failure of the pillar, and the partial failure of the actual pillar as it was pushed into the footwall, was the source of the seismic event. Dilation of rock from the footwall heave decreased as one moves away from the failed pillar (Figure 29 and 30). There were large slabs of rock, which had rotated 90° and were lodged between the footwall and hangingwall, showing the movement of the material along the Prandtl wedge fractures (Figure 31). The depth of footwall fracturing could not be measured.

The hangingwall showed no sign of instability in the footwall heave area down-dip of the failed pillar and were not affected by the seismic shake down. Delicate salt stalactites were seen directly above the footwall heave area and were not affected by shake down from the event. Footwall sand and dust on top of rocks indicated that rocks were thrown up in the event and then the loose material settled over them.

Timber elongates far from the pillar (outside of the radius of footwall heave) showed no signs of fresh failure from the event



Figure 32: The footwall heave zone (approximately 10 m radius) around the failed Merensky Reef pillar. The red arrow indicates the pillar position



Figure 33: Footwall heave around the failed Merensky Reef pillar



Figure 34: Rotation of footwall slabs due to footwall heave

The superimposed UG2 Reef pillar, which was 40 m below the Merensky Reef pillar, was visited. The UG2 Reef pillar was more intact than expected (Figure 35 and 36). Minor shake-down of loose hangingwall rocks from pre - existing fractures and of larger scaled blocks was observed. The pillar was observed to be under minimal stress as only scaling of the edges was seen from relaxation fractures, but this was to be expected from an untouched block of reef. There were no signs of dynamic failure or sudden loading on the pillar or

in the area surrounding the pillar. More damage was observed some distance up-dip from this particular UG2 Reef pillar.

The timber elongates around the pillar showed no sign of loading or failure. Even timber elongates, which had been damaged by a scraper rope, and significantly weakened, were intact.

Stress analysis of this area using IMS Vantage by van Aswegen (2017), showed that a stress reduction of between 1 MPa and 2 MPa were indicated on the UG2 Reef pillar directly below the failed Merensky Reef pillar. Assuming 30 GPa for the UG2 Reef Young's modulus, this stress change translates to a negative strain change of approximately 60 microstrains. This was a reduction in induced stress on the UG2 Reef pillars.



Figure 35: The superimposed UG2 Reef pillar, which had little sign of damage



Figure 36: The superimposed UG2 Reef pillar corner, which had little sign of damage

5.1.2. Case Study 2: 12-21W Merensky Reef and UG2 Reef stopes

On 2 and 3 December 2016, an M1.4 event and a M1.1 event occurred in the vicinity of 12-21W (Figure 37). This area had previously exhibited signs of excessive loading and tensile fractures along the pillar boundaries on the UG2 Reef horizon, which was unusual considering that the area was completely overstoped by Merensky Reef mining. All UG2 Reef mining was stopped in the UG2 Reef panels after these seismic events. A visit was conducted to investigate what had occurred on the Merensky Reef horizon and to identify a possible cause for the higher stope closure rate. The depth of mining below surface of these panels was approximately 654 m and the middling between the Merensky and UG2 Reef was approximately 35 m.

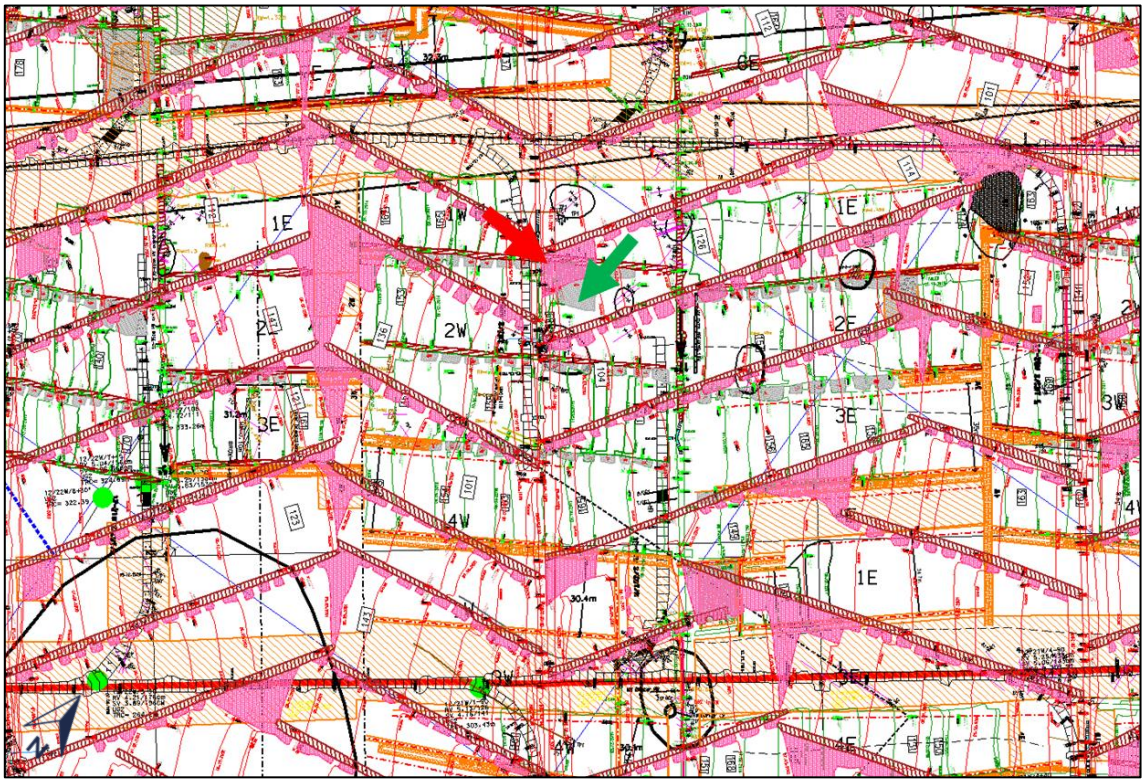


Figure 37: Plan showing the 12-21W UG2 Reef (green) and Merensky Reef stopes (red). The pink hatched areas were the Merensky Reef pillars and the grey hatched areas were the UG2 Reef pillars

The visit was conducted from the down-dip side of the Merensky Reef pillar. Observations made in the Merensky Reef Stopes showed the Merensky Reef hangingwall to be very jointed. Hangingwall detachment was seen and has resulted in major FOGs in the area.

At the area of interest on the Merensky Reef horizon, which was the suspected seismic event source, dynamic failure was observed in the pillar, but the pillar had not completely failed as could be seen by a portion of solid pillar on the one side. Therefore, there was a risk of the pillar building up energy and failing dynamically again. Major FOGs had occurred adjacent to the un - failed portion of the pillar and undulating stress fractures were observed in the hangingwall. These FOGs did not occur as hangingwall detachment, but much deeper into the hangingwall along geological structures. In addition, tensile cracks were observed in the hangingwall in the vicinity of the FOGs. This could possibly indicate pillar punching into the hangingwall.

Similar to what was observed at 11-32W Merensky Reef pillar, the failed portion of the 12-21W pillar was of friable material and shearing was observed along the hangingwall contact. Support damage was observed around the pillar and the FOGs.

Footwall heave was seen by dilation of footwall rocks. Rocks had not been thrown up as observed at the 11-32W failed pillar (Figure 39, 40 and 41). This heave was only observed on the down-dip side of the pillar,

in the failed portion. As this pillar was adjacent to the ASG, most of rock dilation occurred laterally into the ASG (Figure 38).

The in-stope pillars in the area appear to have been suddenly loaded with most pillars shearing on the top contact, which could be seen from ejected rock from these pillars.



Figure 38: Lateral dilation of the Merensky Reef pillar into the ASG



Figure 39: Damage to Merensky Reef pillar



Figure 40: The failed Merensky Reef pillar



Figure 41: Footwall heave around the failed pillar

Observations on the superimposed UG2 Reef pillar in 12-21W 2W panel were conducted directly after the Merensky Reef pillar observations. Surrounding stopes showed minimal shake-down, with most of the scaling occurring on the edges of stable pillars. No hangingwall damage was observed. Highly corroded splitsets were observed to still be intact and not failed. Minimal stress fractures were evident in the pillar and in the hangingwall adjacent to the pillar (Figure 42).



Figure 42: Damage to the superimposed UG2 Reef pillar

UG2 Reef in-stope pillar dynamic failure was seen in 12-21W 4E UG2 Reef panel (Figure 43). A UG2 Reef pillar or remnant in a critical state could be triggered to fail by failure on a nearby Merensky Reef pillar (van Aswegen, 2017). This pillar was longer than the standard dimensions and approximately 15 m from the face position. At the time of the failure no mining personnel were in the stope. The failed UG2 in-stope pillar was crushed into small blocks and no hangingwall shear was observed (Figure 44). The pillar itself failed dynamically as seen by pieces of rock found embedded in the timber elongates and no footwall heave was observed. Only an isolated area was affected. Curved hangingwall fractures around the pillar showed extension stress fractures in the hangingwall. In the vicinity of the pillar, grout packs had reached peak load and failed and bent timber elongates were observed.

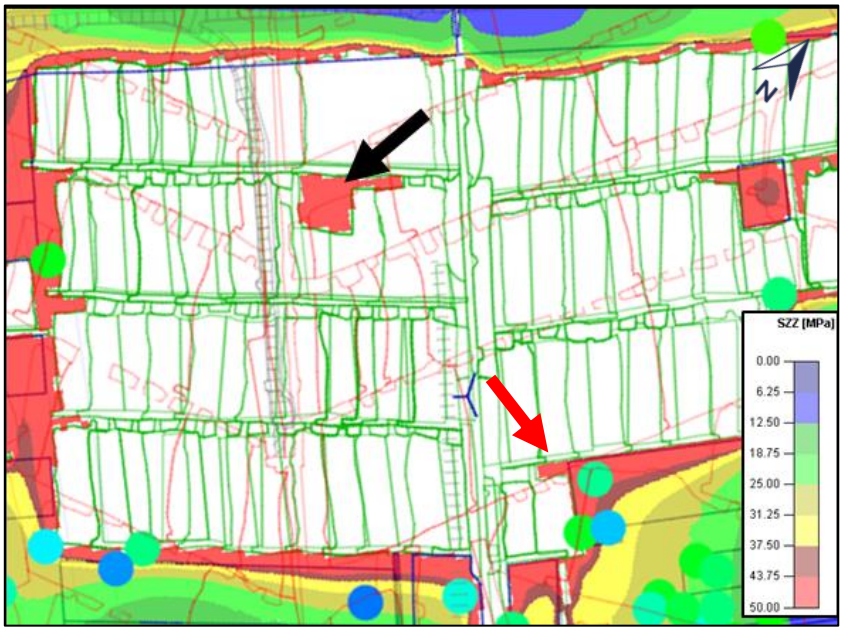


Figure 43: A Plan showing the position of the failed UG2 Reef pillar (red arrow) and the failed Merensky Pillar (black arrow)



Figure 44: The failed UG2 Reef in-stope pillar

5.1.3. Case Study 3: 13-18W Merensky Reef stopes

On 12 December 2017, M2.0, M2.2 and M2.5 events occurred on Merensky Reef elevation in the vicinity of 13-18W stopes. This behaviour was different from the usual seismic events experienced as these very large events occurred as a cluster and could have been a pillar run on the Merensky Reef elevation. Also,

the Merensky Reef stope had not yet been understoped by UG2 Reef. The mining front was within 200 m of this area (Figure 45).



Figure 45: Plan showing the 13-18W UG2 Reef (green) and Merensky Reef stopes (red). The pink hatched areas were the Merensky Reef pillars. The black arrow indicates the pillar of interest. This area has not been understoped by UG2 Reef mining

The 13-18W Merensky Reef crosscut showed shake-down damage indicated by fresh exposed rock. Characteristic sidewall scaling, which usually occurs over time, was shaken loose. This originated from the top corners of the crosscut. Observations made in the Merensky Reef Stopes showed that hangingwall detachment resulted in major FOGs, which could be seen as one enters the stepover to the Merensky Reef raise (Figure 46). This was common with previous observations near Merensky Reef failed pillars. The weight of these detached rocks resulted in cable anchors pulling out and snapped cable anchors were also observed. These cable anchors were expected to hold approximately 20 tons. This behaviour may indicate possible hangingwall ejection.



Figure 46: Hangingwall detachment of the Merensky Reef hangingwall

Closure, of up to approximately 0.8 m, was observed in the centre gully. Highest closure was seen closest to the pillars whilst minimal closure was seen in the centre of the panels (Figure 47 and 48). In-stope pillars all appear to have crushed. The crushed pillars may have been from expected elastic closured and further elastic closure was from hangingwall detachment in the area.

The long, thin triangular pillars adjacent to the raiseline were observed to be fully crushed. Some footwall heave around these long slender pillars and lateral dilation into the centre gully was observed.



Figure 47: High closure of the Merensky Reef panels. Photo taken in the centre gully



Figure 48: Very high closure of the Merensky Reef panels. Photo taken in the centre gully

The suspected M2.5 event source pillar was 3.0 m from the centre gully (Figure 49). In the area of the pillar, hangingwall detachment around the pillar and into the centre gully was observed. The failed pillar showed the fine powder disintegration and slickensided hangingwall top reef contact, similar to which was seen in the pillar from the previous M2.6 event at 11-32W Merensky panel. Footwall heave was observed up to 6.8 m from the "new "pillar face. 0.15 m of closure was measured from the timber elongates in the footwall heave zone, a portion of which may had been initial panel closure.



Figure 49: Crushed (completely failed) Merensky Reef pillars

Many fresh hangingwall tensile cracks were observed around the failed pillar. These cracks were undulating and irregular and not related to any joint set. The large FOGs in the vicinity of the pillar failure indicated some inelastic hangingwall failure instead of only footwall failure, indicating why there was possibly a smaller zone of footwall heave (Figure 50).



Figure 50: The footwall heave around the failed Merensky Reef pillar

5.1.4. Case Study 4: 14-23W UG2 crosscut dynamic failure

In the vicinity of 14-23 crosscut, three seismic events (M0.9, M1.0 and M1.3) were recorded on the UG2 horizon on 23 November 2018 (Figure 51). Further investigation showed that the crosscut protection pillar dynamically failed resulting in the above-mentioned seismic events. 15-23W 1W panel was the only panel blasting and was stopped after the seismic event due to the crosscut dynamic failure and the subsequent risk to mining personnel travelling in this area.

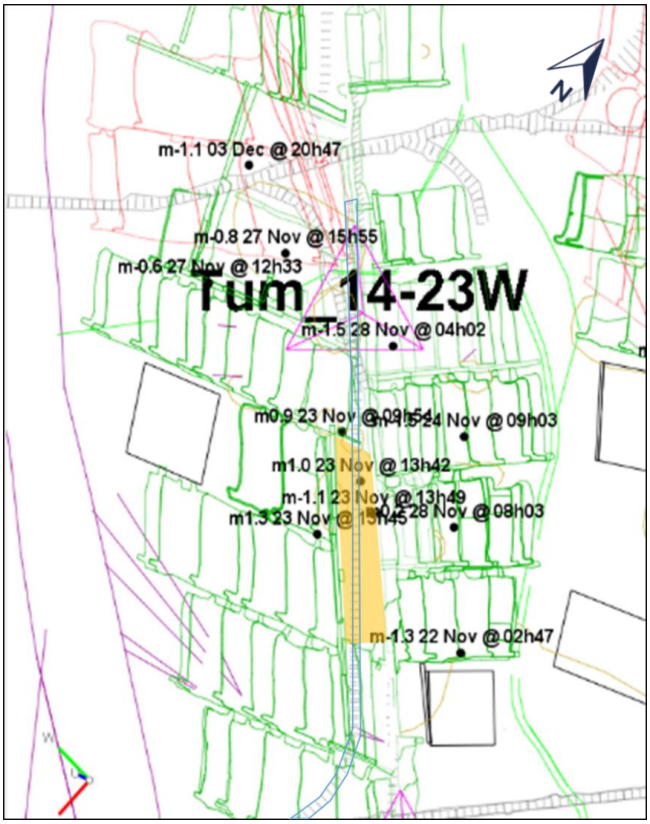


Figure 51: Plot showing all seismic events in the vicinity of 14-23W UG2 crosscut from 20 November 2018 to 31 December 2018. The orange area was the crosscut protection pillar

14-23W UG2 crosscut was approximately 774 m below surface level (Figure 52). The crosscut had been excavated through UG2 Reef from which 14-23W UG2 and 15-23W UG2 raises had been developed from a flat stepover connecting the crosscut and the raiselines. A crosscut protection pillar was planned and development was mined around it to ensure there was no risk from small middlings (vertical distances between two points) between mining of UG2 Reef and the crosscut. This pillar was 14.5 m wide which was larger than the 13 m design for the typical Tumela Mine regional pillars (Figure 51). The Merensky Reef above this area had not been completely mined out, potentially causing higher than expected induced stress.

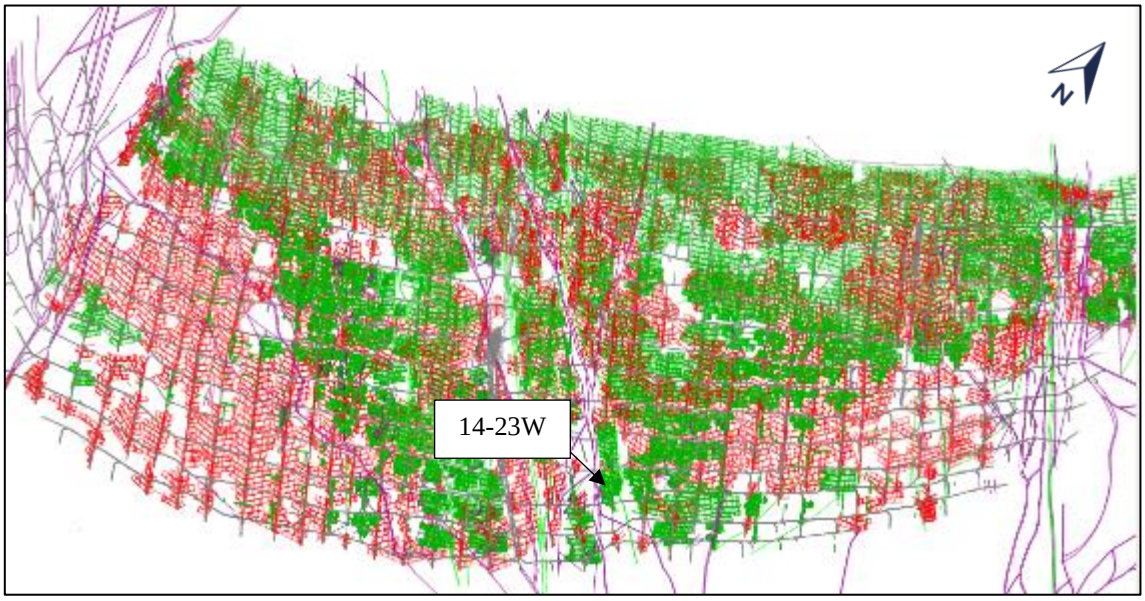


Figure 52: Location of 14-23W UG2 at Tumela Mine

The 23W stoping line was situated between the major Trainsmash fault and a major dyke system. Tectonic stresses from these geological features may have contributed towards the overall field stress of the area. Reverse faults and closely spaced sympathetic jointing were observed in UG2 Reef panels already mined within this area (Figure 53). At 14-23W, the Merensky Reef was partially mined out above the panels at a slow advance per month. The failure to mine out all the panels on the Merensky Reef horizon showed there were poor ground conditions or a stress anomaly in the area, which were unable to be controlled by the support systems available at that time.

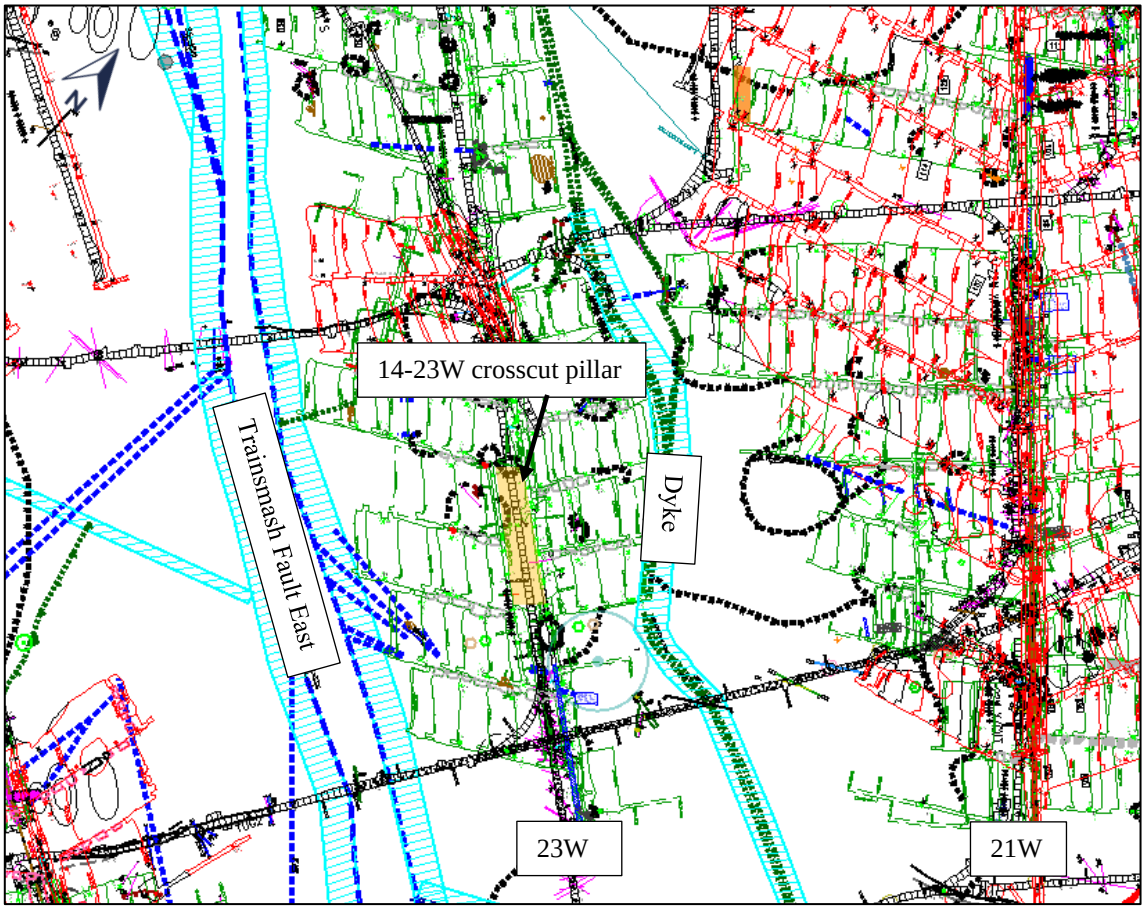


Figure 53: Plan showing the geology in the vicinity of the 14-23W UG2 crosscut. Red outlines showed the mined Merensky Reef areas and green outlines showed the UG2 Reef mined out areas

At time of failure, the average pillar stress (APS) of the pillar was calculated as 116 MPa in IMS Vantage modelling, the width of the pillar measured at 14.5 m. This APS already exceeds the design strength of the regional pillars for the UG2 Reef. The IMS Vantage stress modelling does not take the geological features into consideration and thus the APS calculated could be assumed to be higher than modelled. This puts the crosscut pillar in a potentially very high stress state, which eventually led to the crosscut sidewall dynamic failure.

5.1.4.1. IMS seismic analysis

The S - to - P radiated energy ratio (E_S/E_P) of events could indicate event mechanisms (Kwiatek and Ben - Zion, 2013). Ratios much lower than 10 were usually associated with pure bursting and ratios much higher than 10 with pure slip. For the recorded events, the E_S/E_P ratios calculated were 9.7, 8.2, and 6.3 showing pure bursting as the mechanism for one event and shear failure component for the other two. The damage mechanism, therefore, appears to be “strain bursting” of a portion of the pillar (also possibly within the stope) in all three seismic events at 14-23W.

5.1.4.2. Sequence of events leading to 14-23W UG2 crosscut dynamic failure.

The following sequence of events occurred up to the time of the dynamic pillar failure and the position of these events can be seen in Figure 54:

A	15-23W 1E	Started mining: April 2016. Completed mining: March 2017.
B	15-23W 2E	Started mining: October 2016. Completed mining: February 2017.
C	Re-raise (to mine around the planned crosscut pillar)	Started mining: September 2016. Completed mining: February 2017. Re-raise holed (western side of the crosscut).
D	15-23W 4W	Started mining: April 2017. Completed mining: October 2017.
E	4 April 2017: 3.0 m cable anchors and Osro straps were instructed to be installed in the travelling way/ raise intersection. This was due to a brow, which had formed when the stepover development excavation holed. At the time of this instruction, 3.0 m cable anchors, wire mesh and straps were installed in the travelling way portions from the crosscut to the raise. 27 June 2017: Excessive scaling was observed on the sidewalls of the crosscut between the travelling way and Box one. 3.0 m cable anchors (25 tons) and Osro straps were installed in this area.	
F	15-23W 3W	Started mining: October 2017. Completed mining: June 2018.
G	15-23W 2W	Started mining: December 2017. Completed mining: September2018.
H	June 2018: A winch cubby was blasted for 15-23W 1W. This winch cubby was adjacent to the crosscut in elevation. The spacing between the sidewalls of the crosscut and the winch cubby (on the panel side) was 2.4 m. (It was at this narrowest point in the crosscut where the pillar burst began). 15-23W 3W - Completed mining: June 2018.	
I	15-23W 1W	Started mining: September 2018. Still mining when Seismic event occurred 23 November 2018.

J 22 October 2018: The 14-23W UG2 crosscut and raise was visited after reports that the raise had scaled excessively, and large slabs were blocking the centre gully. After being assessed, an alternative travelling way was created around this area as to leave the slabbing rock as sidewall confinement.

The 14-23W UG2 crosscut sidewall on the eastern side was observed to be scaling excessively and bulging onto the mesh was observed. The western sidewall was observed to be scaling, but not as excessively as the eastern sidewall. (The burst was on the western sidewall). Instruction was given to barricade off the crosscut at the travelling way. 15-23W 1W panel was the only panel blasting.

K 5 November 2018: A start - up risk assessment was conducted in 14-23W UG2 crosscut for the use of the HPE drill rig to drill a hole at the end of the crosscut. At the stepover/travelling way position, cable anchors and straps were observed, but up to the 1.5 m height, the loose slabs of rocks were observed to be scaling onto the rails and sidewalls. On the western sidewall, excessive scaling was observed. It was recommended a net be placed over this area to inhibit any potential rock fall onto the tracks.

15-23W 1W panel was the only panel blasting.

16 November 2018: It was reported that rocks were falling onto the rails from the sidewalls.

L 26 November 2018: The crew of 15-23W P1W reported a fall of ground that occurred at 14-23W UG2 crosscut north. Crew reported the fall of ground (FOG) to be approximately 10 m long with no description of the width of the FOG. The crew stayed at the waiting place to wait for the investigation team to come and do the investigation.

Further investigation showed that the event was a crosscut protection pillar failure resulting in a seismic event of M1.0 and M1.3, which occurred on 23 November 2018 at 13:45. 15-23W 1W panel was the only panel blasting and was stopped after the seismic event due to the crosscut failure.

From the analysis of the timeline, the scaling of the crosscut accelerated after the cubby was blasted for 15-23W 1W UG2 panel and continued as 15-23W 1W UG2 panel was mining. The of mining of 15-23W 1W UG2 panel was very quick with an average advance of 20 m per month (mine call was 13 m per month). 15-23W 1W UG2 panel was the panel with the highest extraction per month at Tumela Mine at the time of the seismic event. This was possibly a result of this lagging panel being highly stressed, which meant a higher advance per blast.

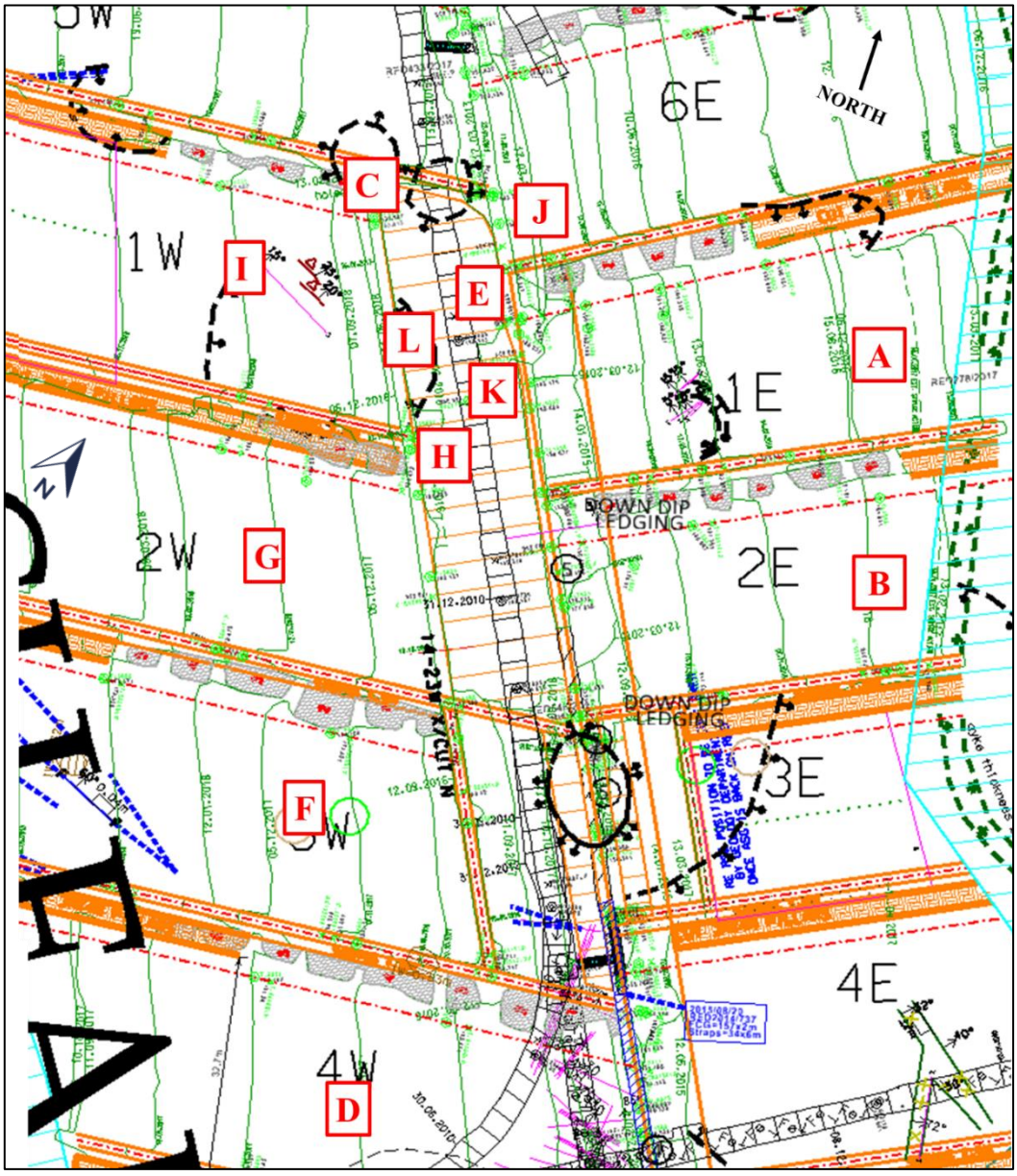


Figure 54: Plan showing the sequence of events before dynamic failure at 14-23W crosscut

5.1.4.3. Underground observations in 14-23W UG2 crosscut and UG2 Reef horizon

On 11 December 2018, a second visit was conducted to the crosscut. In addition, the crosscut pillar (spanning 15-23W and 14-23W UG2 raiselines) was inspected on reef down the re-raise on the western side and up the 15-23W raise on the eastern side of the crosscut. The following observations were made (Figure 55):

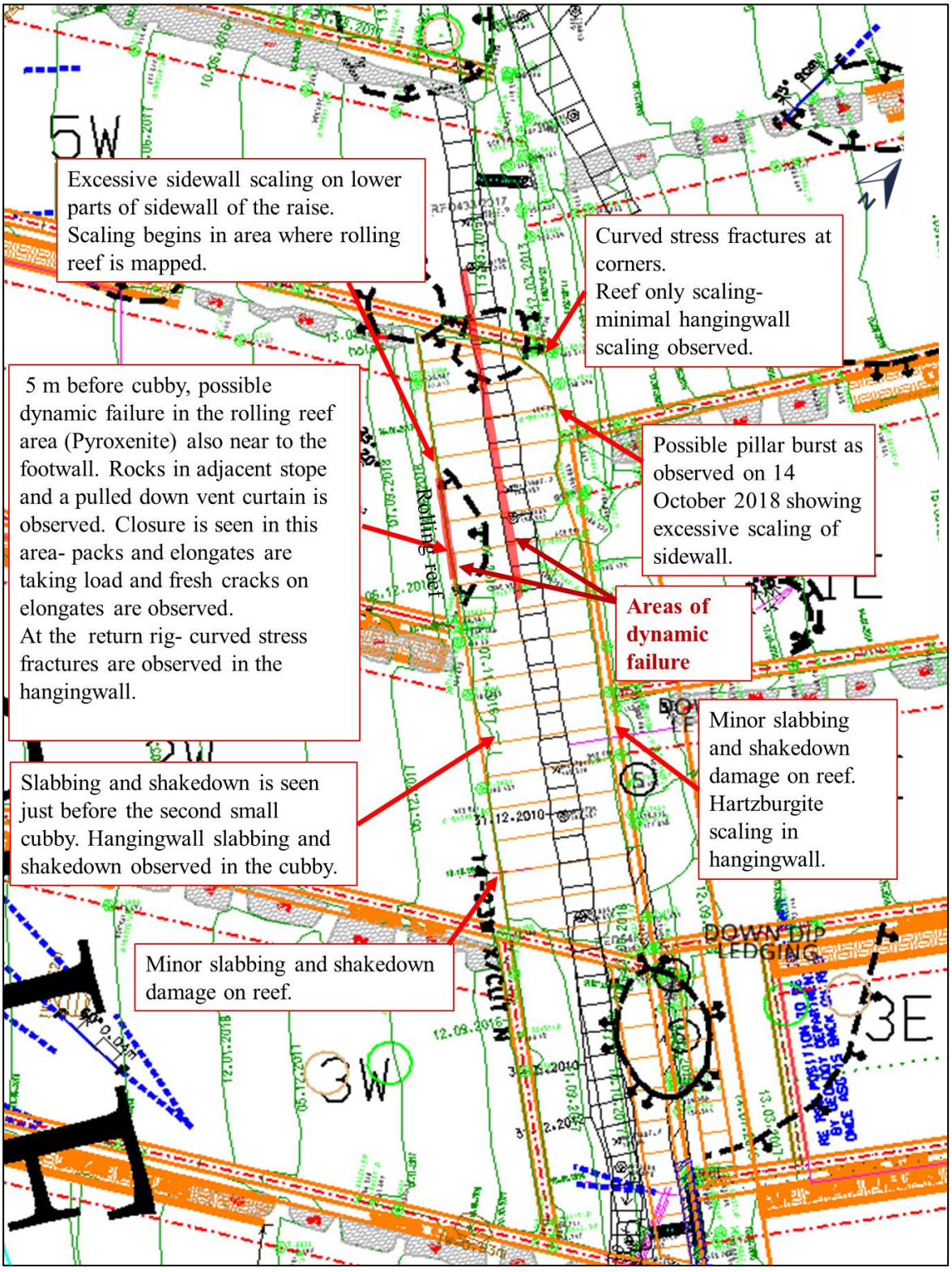


Figure 55: Underground observations on UG2 Reef elevation at the relevant locations

5.1.4.4. MAP3D Numerical model analysis

5.1.4.4.1. Scope of work

To investigate the dynamic failure, a MAP3D model was built and an analysis was conducted on 14-23W UG2 crosscut, which incorporated the mining sequence of events before the dynamic failure of the western sidewall of the crosscut.

A close-up MAP3D analysis over six mining steps was analysed and stress and strain changes were compared. In addition, the model incorporated all possible contributing factors, which may had changed the stress profile of the crosscut leading up to the dynamic failure, namely the winch cubby, the rolling reef and that the crosscut had mined through the UG2 Reef. The UG2 Reef was modelled as on current layout so model analysis could be compared with underground observations. One expects to see current underground conditions replicated as observed.

5.1.4.4.2. Methods

MAP3D was utilized in this research report as three - dimensional replication of underground conditions was required to investigate the interaction of the crosscut with the adjacent mining. This program uses boundary element code, which uses an infinite homogenous elastic medium with defined material properties. To model the stopes and pillars in MAP3D, displacement discontinuity method was used. This was ideal for tabular mining. These areas would be able to yield and behave non - linearly. This was required as would replicate the failure process of the 14-23W UG2 crosscut pillar.
Pillar strength could still be estimated using Salamon pillar strength equation, so a linear elastic model could be used to determine pillar stress. A constraint was that this model was an elastic model so progressive and accumulative failure was not shown.

5.1.4.4.3. Stability parameters

The extension criterion (Stacey, 1981) and the brittle Hoek - Brown (Martin *et al*, 1999) were two of the failure criteria, which had been observed to observe the failure processes in hard rock mines.
The empirical brittle Hoek - Brown failure criterion was applied to the panels to investigate the failure mechanisms of pillars as it was a continuum model. The Mohr - Coulomb criteria was applied to the crosscut as failure criteria for elastic analysis. These parameters were determined from previous laboratory tests conducted on core from the Amandelbult area.

5.1.4.4.4. Mining steps

The following mining steps were considered in the model:

- Mining step 1 (Figure 57) - all areas mined out until the first scaling was observed in the crosscut (April 2017) (red).
- Mining step 2 (Figure 58) - all panels were mined out except 15-23W 1W (dark blue).
- Mining step 3 (Figure 59) - 15-23W 1W Winch cubby was mined out creating a 2.4 m pillar between the crosscut and the cubby (pink).
- Mining step 4 (Figure 60) - month 1 of mining of 15-23W 1W (September 2018) (light green).
- Mining step 5 (Figure 61) - month 2 of mining of 15-23W 1W (October 2018) (dark pink).
- Mining step 6 (Figure 62) - month 3 of mining of 15-23W 1W (up to the time of the seismic event) where the face was stopped on 23 November 2018 (light blue).

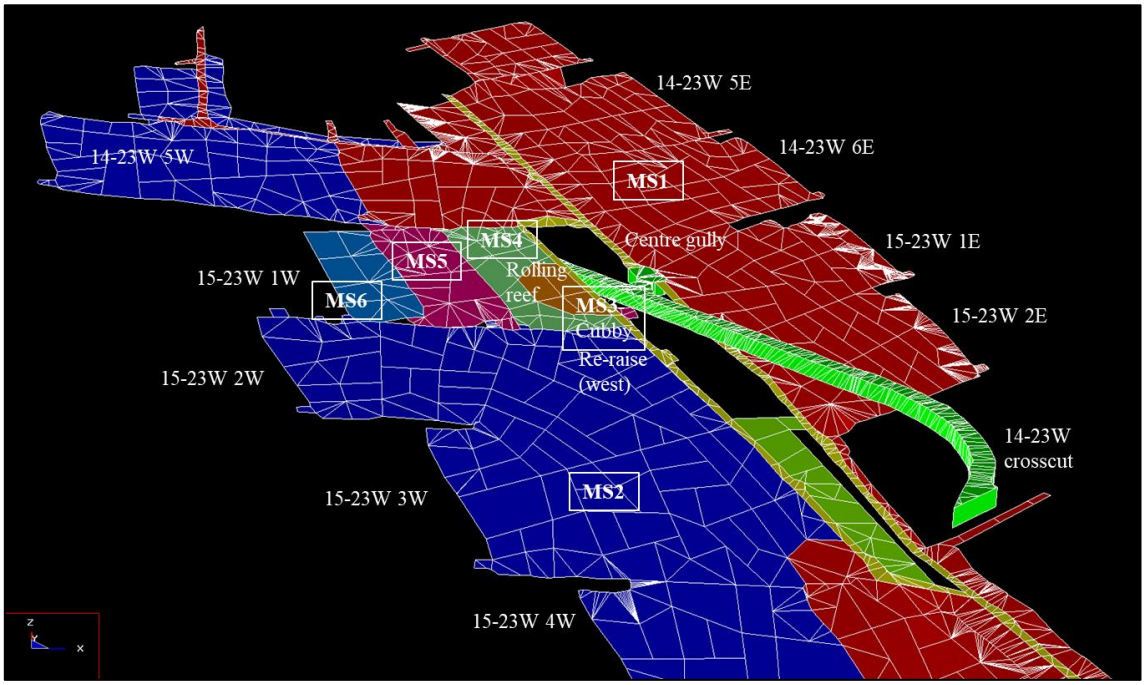


Figure 56: MAP3D model of the 14-23W UG2 crosscut indicating the mining steps used in the numerical modelling analysis (looking North)

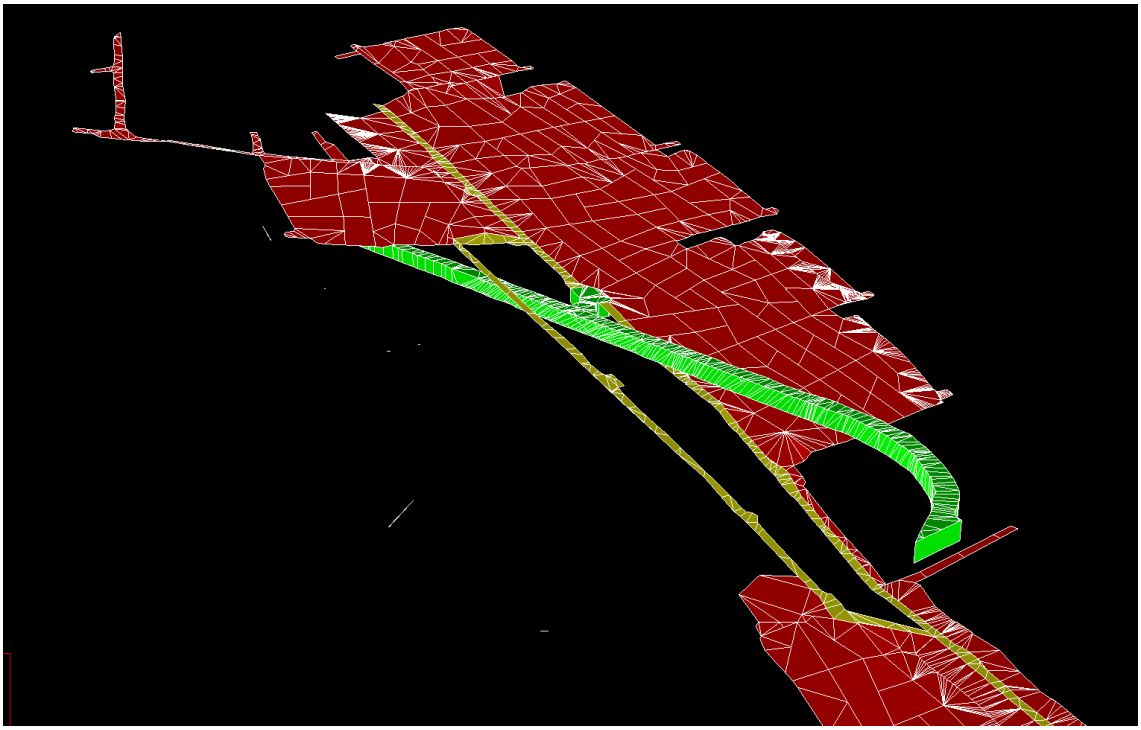


Figure 57: Mining step 1 - all areas mined out until the first scaling is observed in the crosscut (April 2017) - looking North

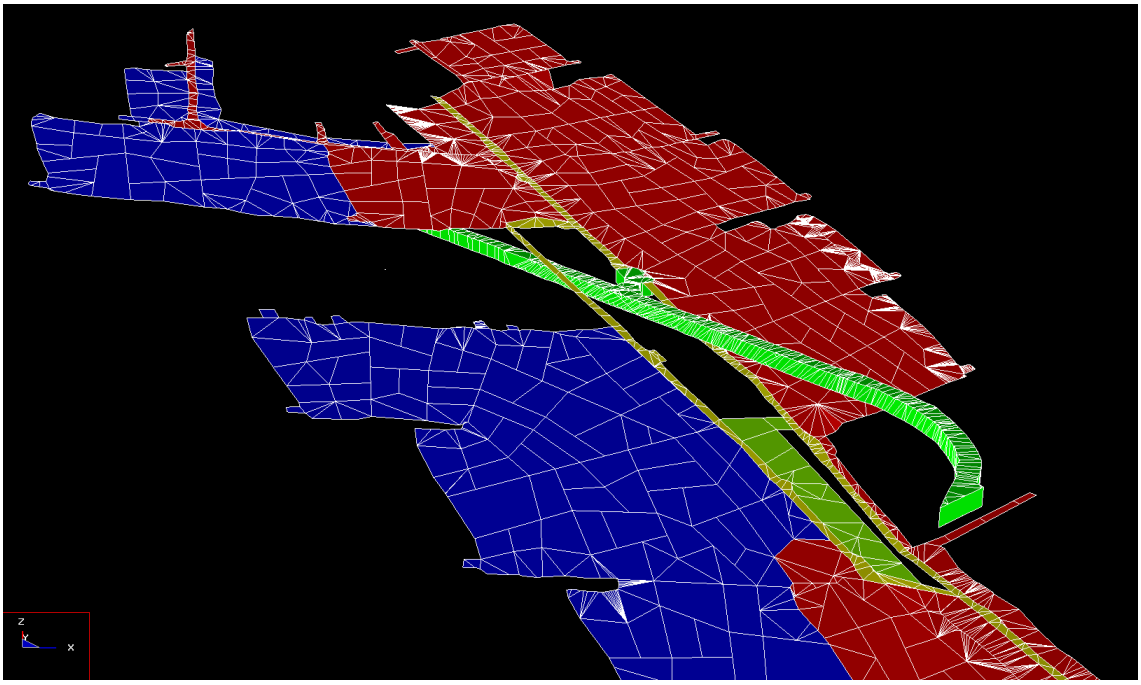


Figure 58: Mining step 2 - all panels are mined out except 15-23W 1W - looking North

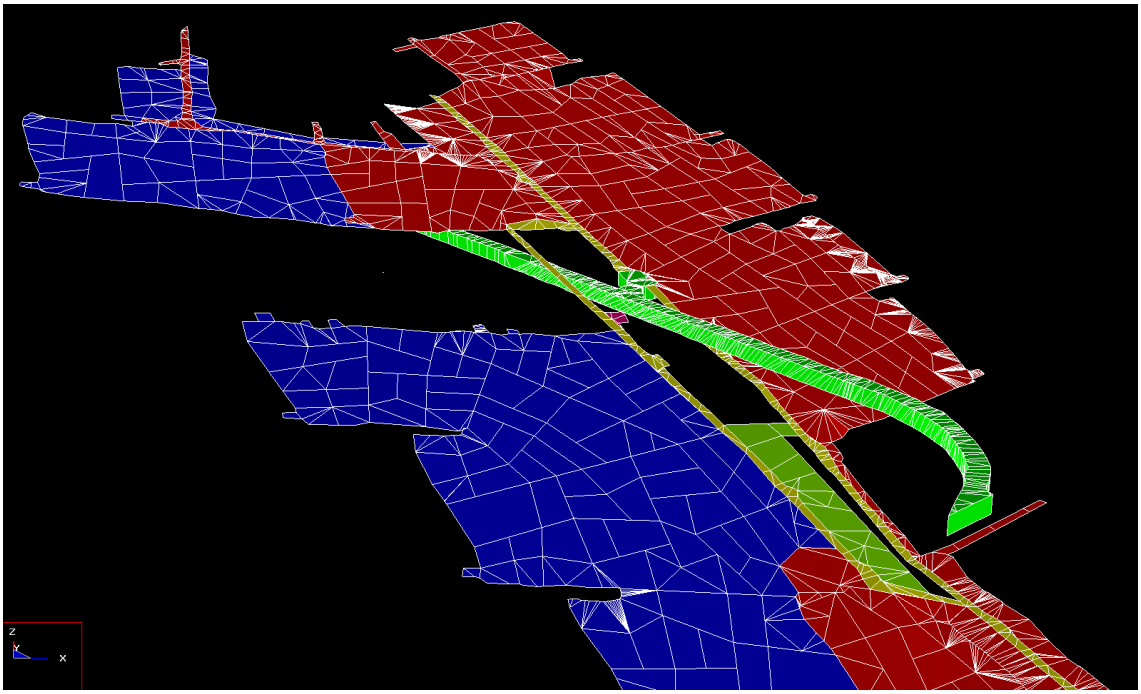


Figure 59: Mining step 3 -15-23W 1W Winch cubby is mined out - looking North

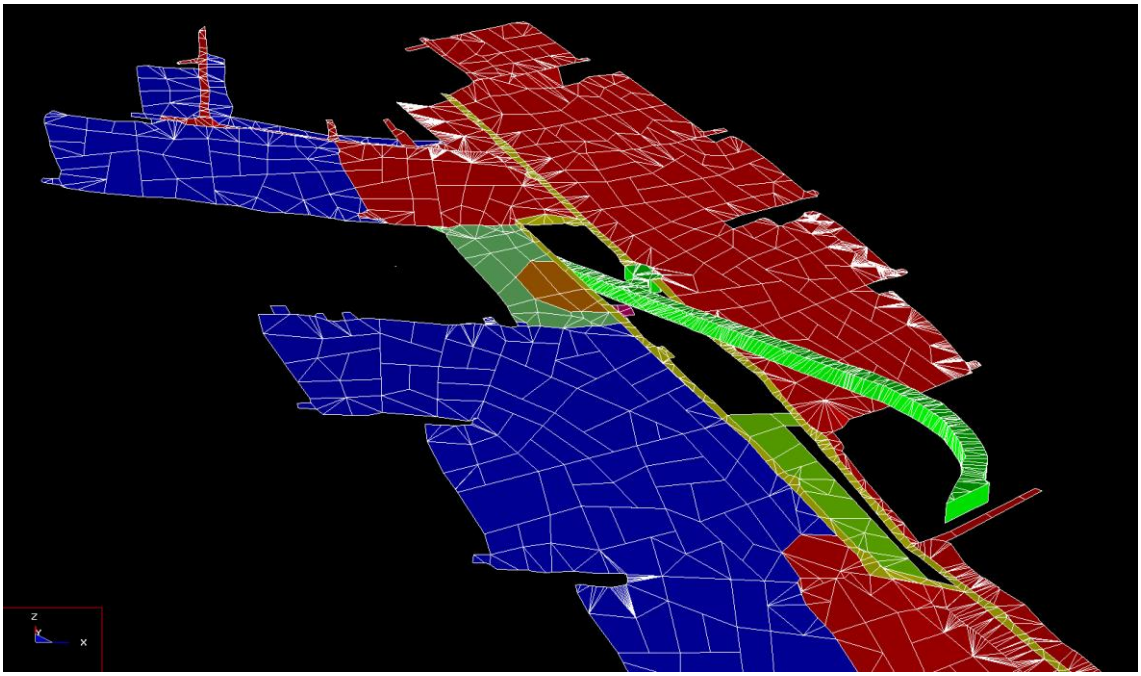


Figure 60: Mining step 4 - month 1 of 15-23W 1W - looking North

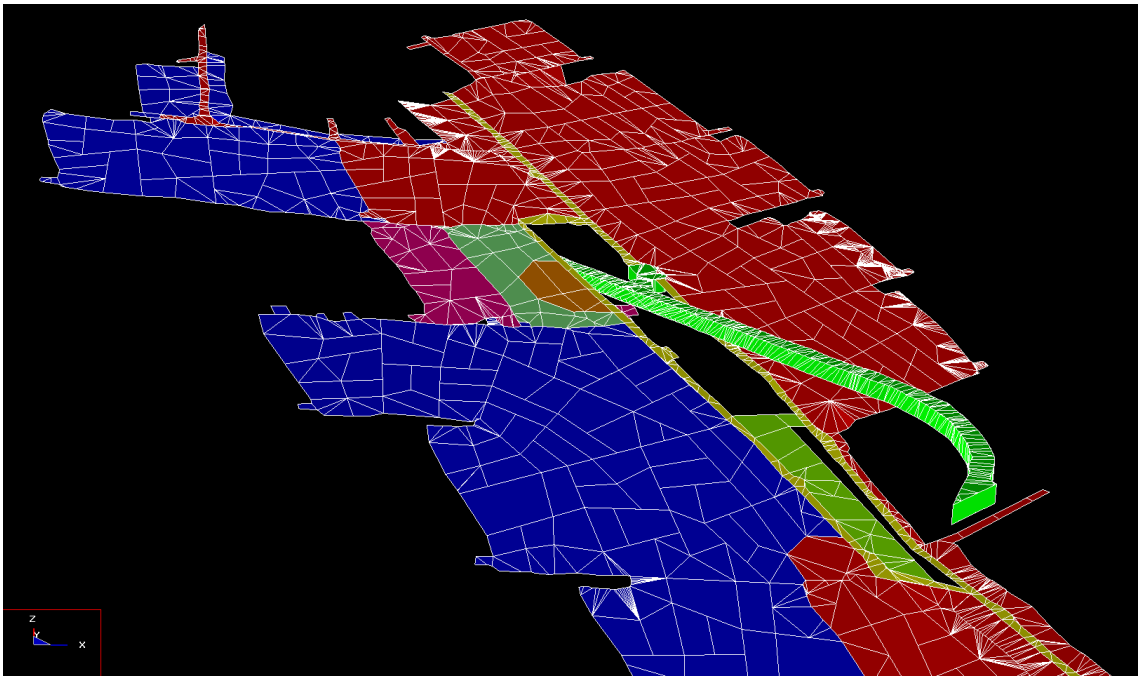


Figure 61: Mining step 5 - month 2 of 15-23W 1W - looking North

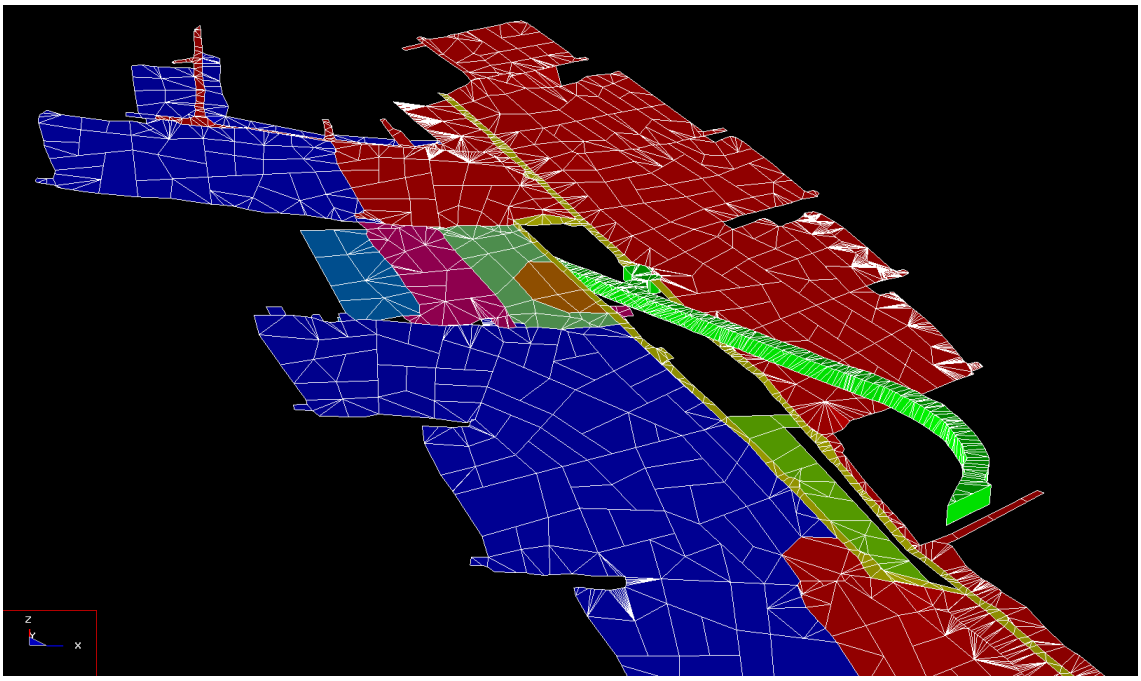


Figure 62: Mining step 6 - month 3 of 15-23W 1W (up to time of seismic event) where the face was stopped on 23 November 2018- looking North

5.1.4.5. Comparison of underground observations to MAP3D numerical modelling analysis

Conditions, which may had had an influence on the stress exerted on the crosscut, were considered in the building and analysis of the MAP3D model. This included the sequence of mining, the mined - out winch cubby, the rolling reef in 15-23W 1W panel and crosscut, and that the crosscut mined through the UG2 Reef.

Underground observations showed possible dynamic failure in the re-raise on the west side of the crosscut pillar and the adjacent areas in the crosscut. Excessive scaling was observed approximately 10 m before the reef intersection (step over position). These higher stress areas observed underground have been replicated in results from the MAP3D numerical model (Figure 63).

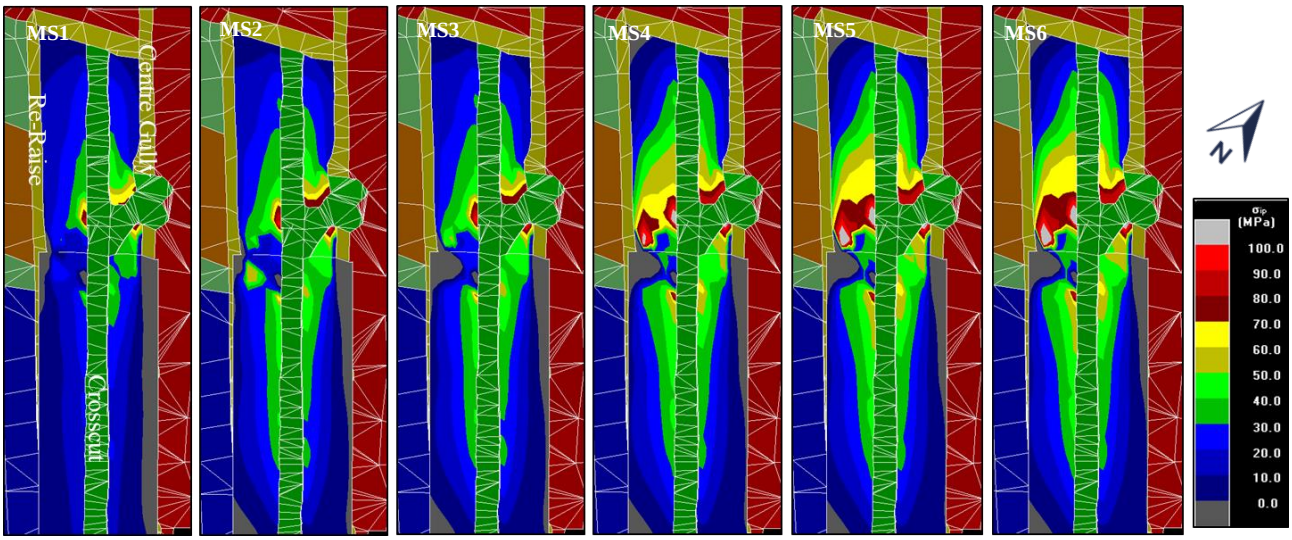


Figure 63: The stress changes (Sigma 1- in plane) made over the six mining steps as shown in MAP3D

As the western panels began to mine, stress accumulation was observed at the travelling way position and in the western sidewall. At this time, secondary support was installed. As the western panels progressed, this area of higher stress built up, yet little change was observed in the stress level as the cubby was mined out (mining step 3). The highest stress changes were seen as the 15-23W 1W panels began to mine (mining step 4 -6). The highest stresses calculated by the model was in the same area of dynamic failure observed in the crosscut and the re-raise underground. In addition, another pocket of high stress was observed from the modelling results where excessive scaling of the crosscut was observed in the week prior to failure (approximately 10 m before the step over).

5.1.4.6. Rockwall Condition factor

Rockwall condition factor (RCF) was the ratio of the maximum tangential stress to the strength of rock mass (Jager and Ryder, 1999):

$$\mathrm{RCF} = \frac{3\sigma 1 - \sigma 3}{\mathrm{F}.\,\sigma \mathrm{c}}$$

σ_1- major three - dimensional field stress components (major subsidiary principle stress) acting normal to the long axis of a tunnel (vertical). 29.8 MPa used for this analysis.

σ_3- minor three - dimensional field stress components (minor subsidiary principle stress). 35.8 MPa used for this analysis for a k - ratio of 1.2.

σ_c - uniaxial compressive strength of rock. 150 MPa was used as an average for the surrounding rockmass.

F - empirical the rockmass condition factor (for competent rock F = 1). Taking into consideration that the rockmass in the crosscut was fractured from blasting and containing minor jointing, a value of 0.8 for F was to be assumed for 14-23W UG2 crosscut and used in the model.

An RCF value of less than 0.7 would indicate “excellent” ground conditions and an RCF exceeding 1.4 would indicate “poor” ground conditions where areal support and increased support resistance would be required (Vieira *et al*, 2005). The RCF calculated in MAP3D assumes the rockmass was intact therefore, the empirical rockmass condition factor (F) was 1 (Vieira *et al*, 2005). Taking into consideration that the rockmass in the crosscut was fractured from blasting and containing minor jointing, a value of 0.8 for F was to be assumed for 14-23W UG2 crosscut and used in the model. This would result in an approximately 20 percent increase in the RCF value of the MAP3D calculated result.

In step 1, when scaling was first noticed on the sidewalls, the RCF value was approximately 0.9. At failure at mining step 6, at the same point of interest, the RCF had increased to 1.2. (Figure 64).

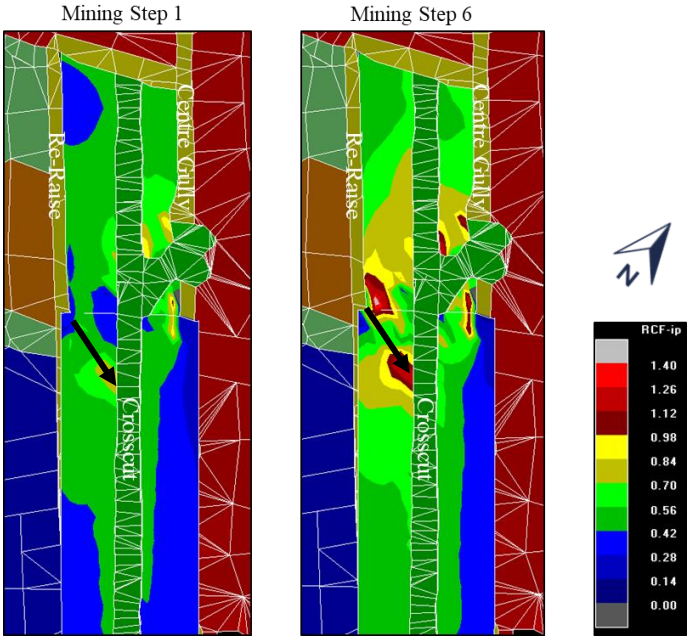


Figure 64: MAP3D plot showing the RCF at step 1 (when scaling was first noticed on the sidewall) and at step 6 (dynamic failure). The black arrows indicate the point of interest (the failure area)

The values of RCF calculated by the model fall within the "average ground conditions (0.7<RCF<1.4) range. For areas where there were anticipated stress changes (such as the 14-23W UG2 crosscut), according to Jager and Ryder (1999), primary support would require to be "fully grouted tendons or steel ropes, more than 1.8 m in length, on a basic 2.0 m or 1.5 m pattern" and secondary support would be "medium strength rope lacing and moderate strength wiremesh integrated with primary support tendons". At 14-23W UG2 crosscut, the area of the dynamic failure was supported by 3.0 m long cable anchors, which were pre - stressed to 10 tons, 2.0 m full column grouted tendons and steel "Osro" straps. With reference to the RCF equation, this would be more than enough.

But there are too many variables to determine whether the support was sufficient as the tectonic stress of the reef roll is not known. The seismic events occurred in the following order: M0.9 at 09:54:31; M1.0 at 13:42:48 and M1.3 at 13:45:56. The M0.9 event did not occur in the crosscut, but instead in the vicinity of the rolling reef on the reef horizon. This may have resulted in the crosscut being dynamically loaded and two events occurring in the crosscut approximately four hours later.

5.1.4.7. Contributing factors towards 14-23W UG2 crosscut failure

5.1.4.7.1. Rate of stress change and extraction

From the time when 15-23W 1W mined consistently (8 September 2018) to the time of dynamic failure on 23 November 2018, 76 days had passed. A total of 1519 m^2 was blasted in 15-23W 1W in this time. This

was an advance of approximately 20 m a month (mine call was an average of 13 m per month). As determined by the model, an average increase of 30 MPa was induced in the rockmass in this period (Figure 65).

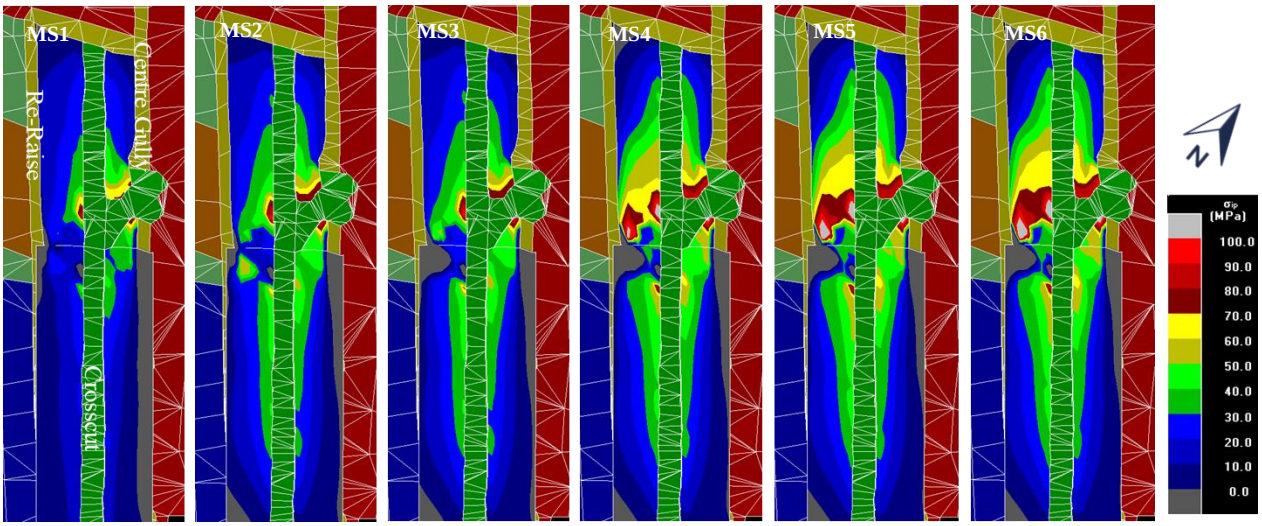


Figure 65: The stress changes (Sigma 1- in plane) made over the six mining steps as shown in MAP3D

As highlighted previously, local mine stiffness (or the loading system) was dictated by parameters such as elastic modulus, thickness, and extraction ratio (Kaiser *et al*, 2010). If the local mine stiffness were high in comparison to the post peak stiffness of the pillar, the burst would not be violent as energy was absorbed by rock fracturing in the pillar. When more energy was put into the failing pillar in comparison with which is absorbed by the fracturing process, excess energy results in violent pillar failure (Maybee, 2000). Due to the rate of mining, the stresses did not have time to be absorbed and redistributed in the fracturing process and thus, the crosscut acted to weaken the pillar and dynamic failure occurred. As the extraction ratio increases to approximately 75% or more, the system became "softer" and the possibility of a violent failure increased (Vardar *et al*, 2017). The 15-23W panels had an extraction ratio exceeding 80 %.

5.1.4.7.2. Extent of failure

An anomaly at 14-23W UG2 crosscut was the extent of the dynamic failure. The dynamic failure extended a considerable distance from the reef intersection to under the mined out UG2 Reef, which was an area with less stress and possibly less fractured. The area of the pillar burst was supported by 3.0 m long cable anchors, which were pre - stressed to 10 tons. The rate of degradation from an intact to failed rockmass strength is dependent on confinement, and rock may be significantly stronger than previously anticipated (Kaiser *et al*, 2010). The installation of the pre - stressed cable anchors may had contributed to the dynamic failure in the crosscut as " cable anchors preserved the "elastic" condition of rock, allowing it to store more energy (and

burst), whereas the unsupported area could develop failure progressively without nearly as much energy stored" (Stacey, 2019). This could potentially explain why the area of dynamic failure extended further than what the model had predicted and even into a de-stressed area. As stated in Kaiser *et al*. (2010), "at low confinement, tensile crack initiation and propagation is the dominating failure process. Heterogeneities in the rockmass favour tensile conditions even in an overall compressive setting and thus promote the unstable propagation of tensile cracks leading to spalling. At higher confinement, the unstable propagation of tensile cracks was inhibited and thus shear bands (with an internal tensile fracture structure) would form, leading eventually to failure."

5.1.4.7.3. Mining sequence

Figure 66 depicts the panels mining at the time of the 14-23W UG2 crosscut pillar dynamic failure. As indicated by the red star in the diagram below, the 15-23W 1W panel was the panel mining most out of sequence and closest to the shaft. This would indicate that panels this far behind the mining face were under considerably higher stress conditions than the panels mining in the correct sequence.

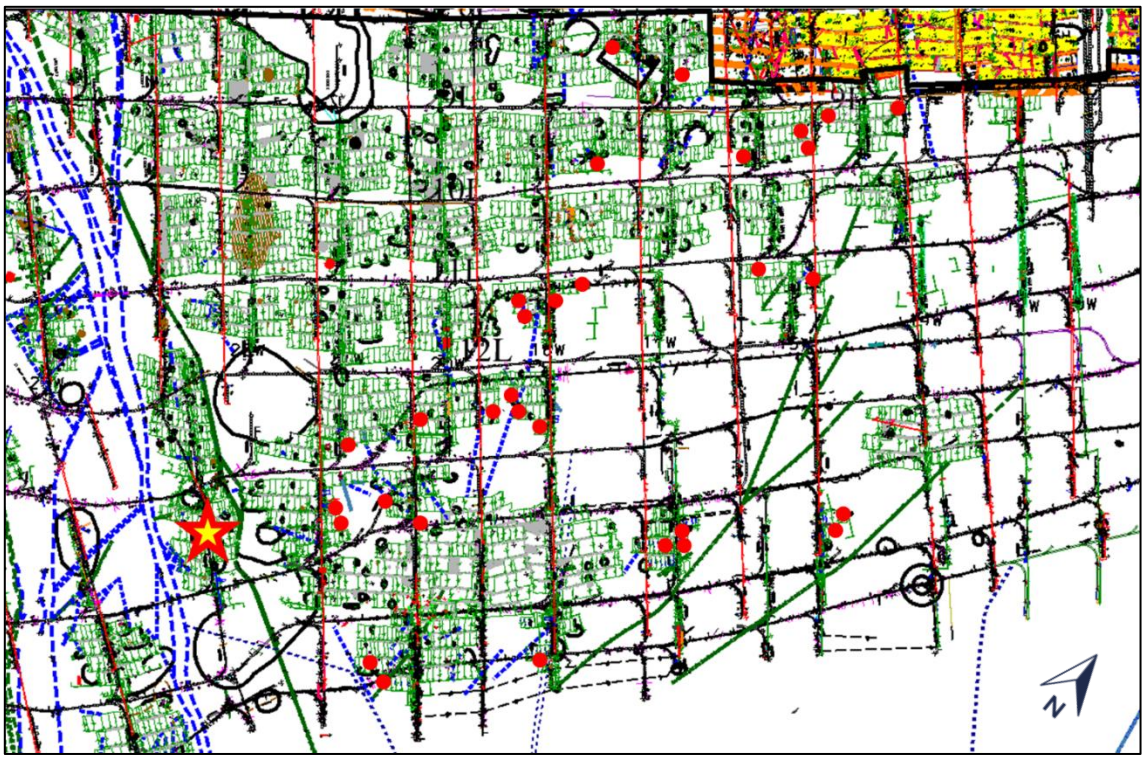


Figure 66: Plan showing 15-23W 1W panel (red star) and the mining panels at the time of the crosscut dynamic failure (red circles)

The sequencing of mining was incorrect and poorly controlled at the 15-23W stope. The panels should have been mined in an underhand configuration with the top panels leading the mining of the bottom panels and

with acceptable leads and lags between the panels. Instead the western panels were mined first and the panels were mined in a sequence from the bottom towards the top. This placed the crosscut pillar under higher than normal stresses as a "remnant" was created and with the accelerated rate of mining of 15-23W 1W, the stresses were unable to redistribute effectively.

5.1.4.7.4. Sensitivity analysis

A sensitivity analysis, where certain prominent inputs were excluded, were analysed though the MAP3D modelling and each result was compared to the baseline model, where all conditions observed underground were considered. By not considering certain aspects (such as the UG2 Reef intersection) in the model, the effects of each scenario change could be clearly shown through the model. All models were analysed from mining step 3 to mining step 6 (winch cubby was mined out to crosscut dynamic failure) as this was where the highest stress change was recorded from the baseline model.

The following scenarios were considered, and the results analysed:

a) Scenario 1: Baseline model

The model was run with all geological factors and excavations considered at the time of failure. This was the "baseline model", which the other scenarios were compared against. The baseline model depicts the crosscut already having been being developed through the UG2 Reef plane, the winch cubby blasted on reef for the mining of 15-23W 1W panel and the intersection of the rolling reef (Figure 67).

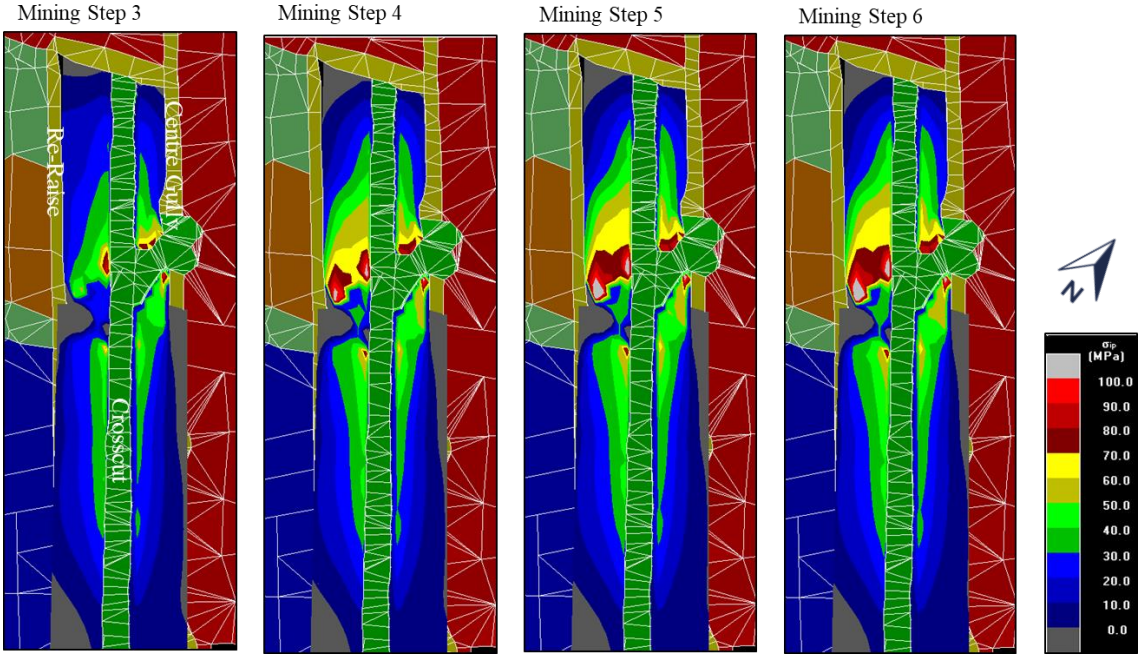


Figure 67: Scenario 1 Baseline model - Stress changes from the winch cubby being blasted between mining steps 4 to 6

b) Scenario 2: The winch cubby was not blasted.

The blasting of the winch cubby was conducted in a breast configuration into the UG2 Reef hangingwall as the reef was undulating (rolling reef). This was at the same elevation as the crosscut. This possibly caused fractures to extend into the crosscut pillar and into the crosscut itself. After the winch cubby was completed, there was only a 2.5 m pillar between the cubby and the crosscut, which was possibly highly fractured. This would had caused a zone of very high stress adjacent to this on which dynamic failure could had potentially begun (Figure 68).

Results showed that there was little stress change and change in stress distribution between the baseline scenarios and if the cubby was not mined out. It could be concluded that the presence of the cubby was a small contributing factor on the dynamic failure of the crosscut (Figure 68).

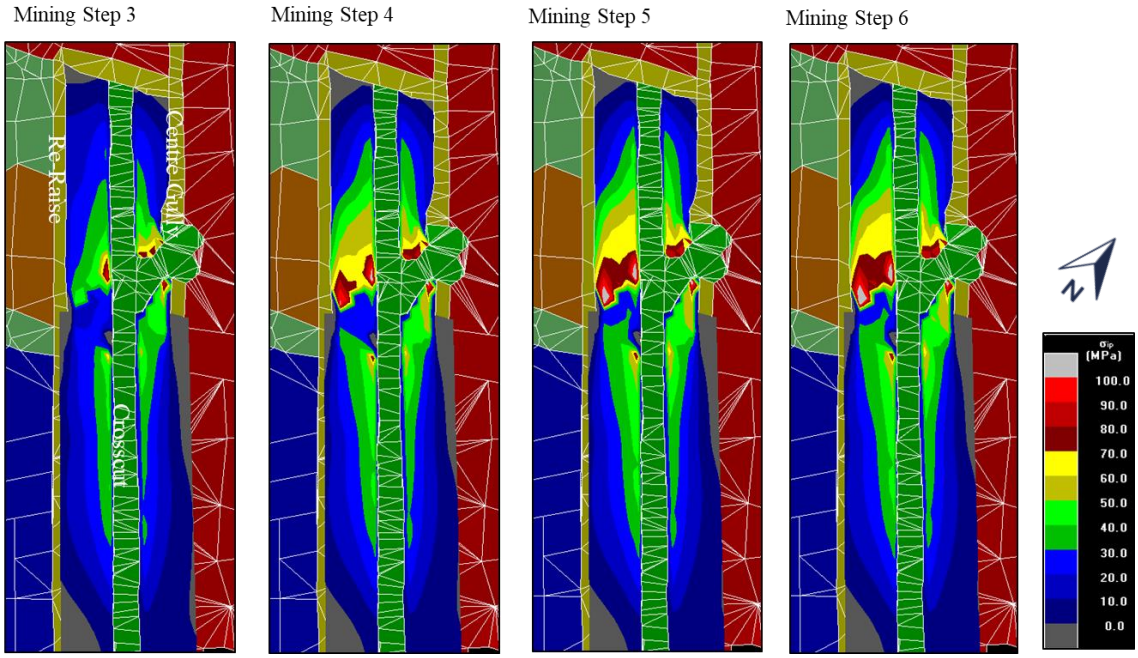


Figure 68: Scenario 2- Stress changes from the winch cubby not being blasted between mining steps 4 to 6

c) Scenario 3: No UG2 Reef intersection in the crosscut, the winch cubby was mined out.

The crosscut was mined through the UG2 Reef and the travelling way was developed perpendicular to the crosscut. The portion of the crosscut, which failed dynamically was below the UG2 Reef and the portion, which scaled, was above the UG2 Reef (Figure 69).

This scenario modelled as there being no rock type change from pyroxenite hangingwall to UG2 Reef chromitite, then pyroxenite footwall. The crosscut was modelled to have mined through pyroxenite only.

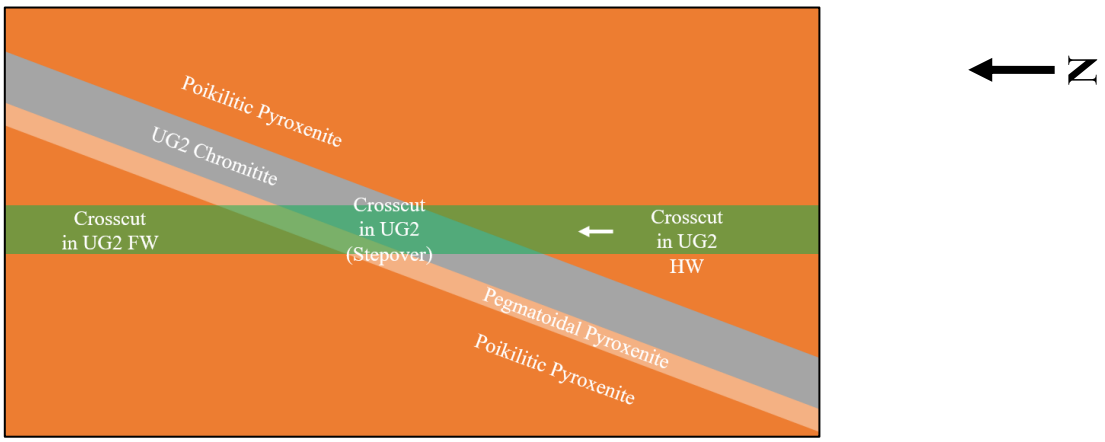


Figure 69: Diagram showing how the crosscut mines firstly through the UG2 Reef hangingwall, the UG2 Reef and then the UG2 Reef footwall

Results showed that a rock type change had a significant effect on the stress distribution and the level of stress in the crosscut and the re - raise. The stress decreased significantly from between 70-90 MPa to between 50 - 60 MPa once the rock type change aspect was removed. There was still a slight increase of stress by the mined - out winch cubby, but this was more due to geometry of the winch cubby (Figure 70).

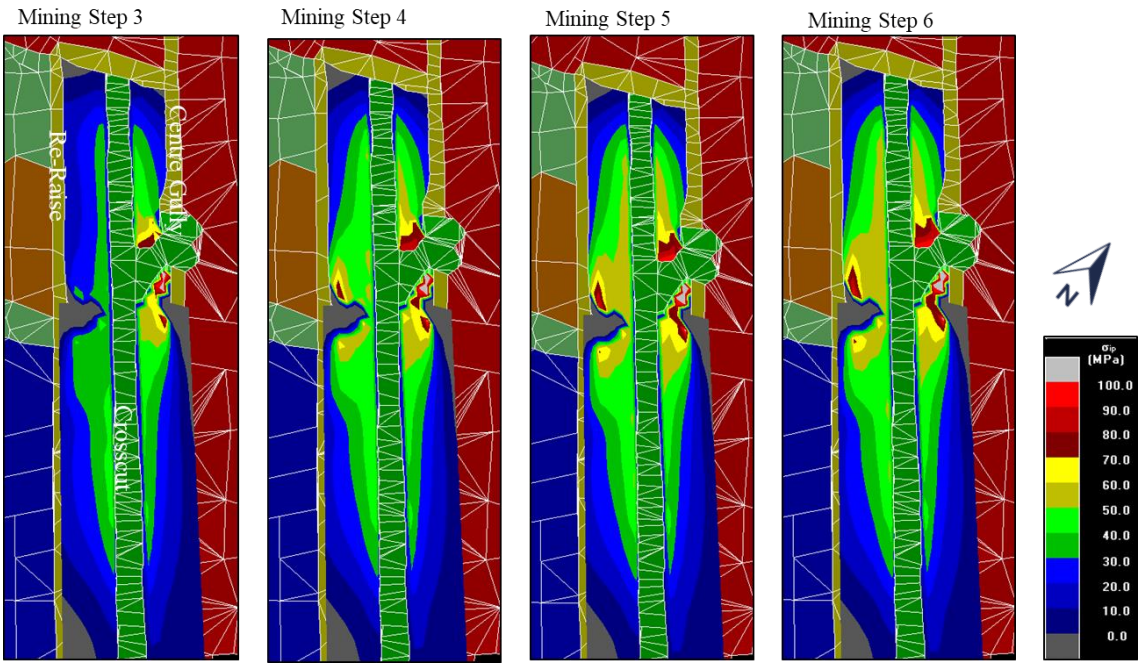


Figure 70: Scenario 3- Stress changes from no UG2 Reef/crosscut intersection (no rock type change) between mining steps 4 to 6

d) Scenario 4: No rolling reef present, UG2 Reef was present and the winch cubby was mined out.

Rolling reef in the panel and western re-raise caused pyroxenite to be exposed in the re - raise. It was observed that pyroxenite had been a possible source of the seismic event as the pyroxenite on both sides of

the crosscut pillar and in similar positions had failed dynamically. The pyroxenite was a rock of a higher strength, brittleness, and stiffness than the UG2 Reef chromite.

The rolling reef (and pyroxenite) present in the re-raise and potentially affecting the crosscut was taken out of the model for this scenario. Again, there was no rock type change from a less stiff UG2 Reef to a stiffer pyroxenite both in the crosscut and the western re-raise considered.

Results showed that, when the rolling reef rock type change was removed and the softer UG2 Reef was put in place of the stiffer Pyroxenite, this showed the most notable change in stress distribution and stress amount. The change in stress ranges from between 70 MPa - 90 MPa (Pyroxenite considered) to between 40 MPa - 50 MPa once the rock type change aspect was removed. There was still an increase of stress of up to approximately 100 MPa in the crosscut at the UG2 Reef intersection, but little stress in the re-raise (Figure 71).

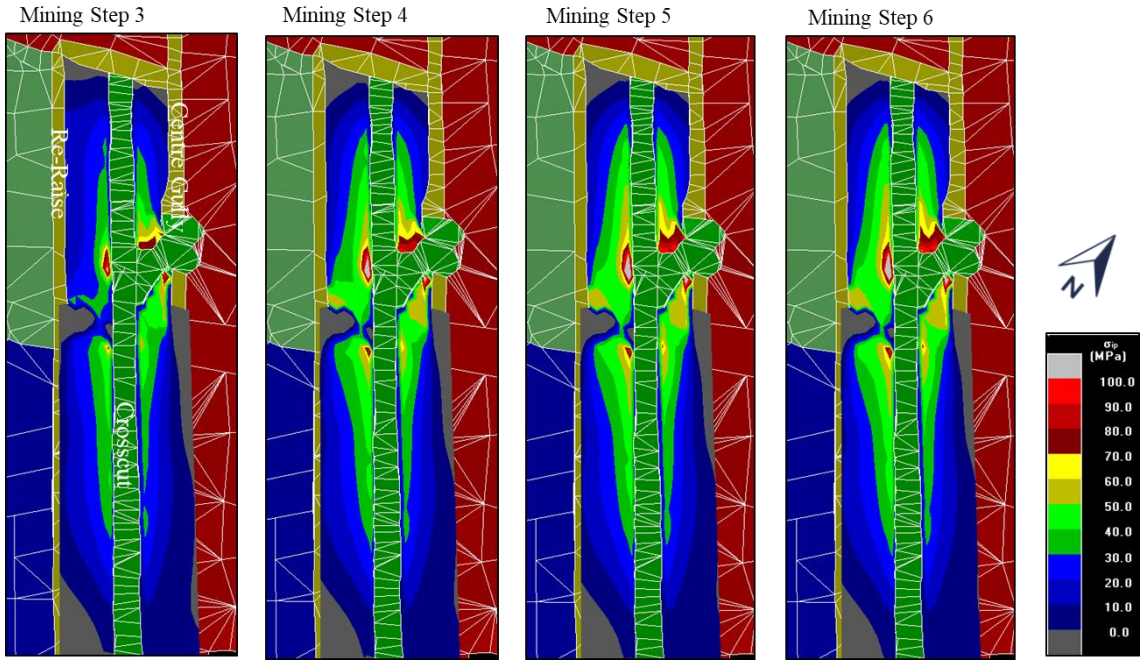


Figure 71: Scenario 4- Stress changes from no rolling reef present (no rock type change) between mining steps 4 to 6

5.1.4.8. Summary

Analysis of all possible influences on the 14-23W UG2 Reef crosscut which may have led to the dynamic failure have ben summarised in Table 2:

Table 2: Table showing a summary on the effects of changes to the baseline model on the stresses as observed in the crosscut

Sensitivity and plan analysis	Possible influence causing the crosscut dynamic failure

Winch cubby not blasted and no small pillar between the re-raise and the crosscut created.	Minimal
No UG2 Reef/crosscut intersection i.e. no rock type change from UG2 Chromitite to pyroxenite, only solid pyroxenite.	Significant
No rolling reef present i.e. no rock type change from UG2 Reef to pyroxenite and back to UG2 Reef.	Significant
Rate of mining of the 15-23W 1W panel.	Moderate
Local mine stiffness influenced from the extraction ratio.	Significant
Mining sequence (regional) i.e. mine was not being mined in a proper underhand configuration and the 14-23W panels were mining a "remnant" of UG2 Reef.	Significant
Mining sequence (local) i.e. the panels in the stope were not mined in the proper underhand configuration and leads and lag distances were not enforced.	Significant
Tectonic stresses from the position of the crosscut between a major dyke and a major fault system.	Significant

Non - adherence to proper mine practices in higher stressed areas potentially could have resulted in a loss of life. Identifying high risk areas on the mine is essential in maintaining a safe working environment for underground personnel.

5.1.4.9. Underground Photographs

The following photos show the extent of the damage in 14-23W UG2 crosscut. The position of the damaged can be referenced in Figure 72.

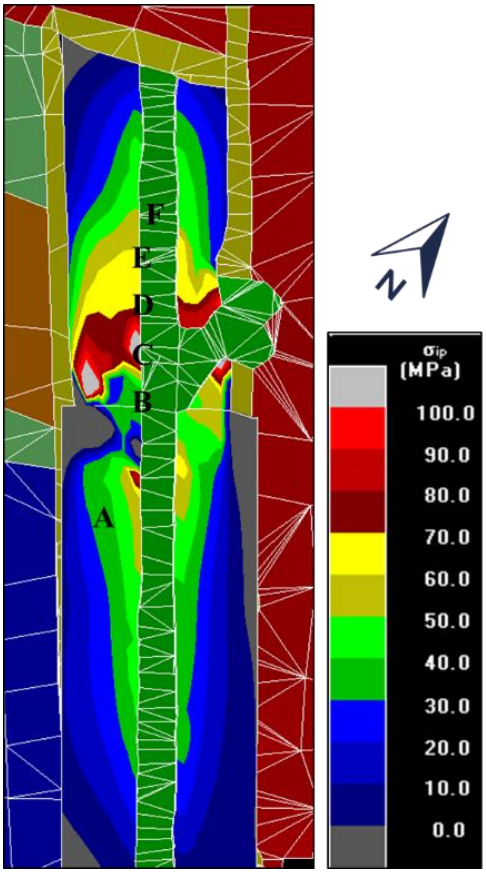


Figure 72: The locations of where the photos were taken in 14-23W crosscut



Figure 73: 14-23W UG2 crosscut - western sidewall - Approximately 20 m from travelling way. Shake-down damage. This sidewall was previously reported to be scaling excessively. Net was installed as a remedial measure



Figure 74: 14-23W UG2 crosscut at the entrance to the travelling way to the raise - western sidewall



Figure 75: 14-23W UG2 crosscut - western sidewall



Figure 76: 14-23W UG2 crosscut - western sidewall



Figure 77: 14-23W UG2 crosscut - western sidewall. The secondary support in this area was highly tensioned as the cable anchors were observed to be pulled into the sidewall. This sidewall was very unstable



Figure 78: 14-23W UG2 crosscut

5.1.4.10. Numerical modelling input parameters, assumptions and constraints

The input parameters were determined from laboratory core testing of the associated rock types considered in the model. The figures below show the input parameters used for the MAP3D numerical modelling of 14-23W crosscut:

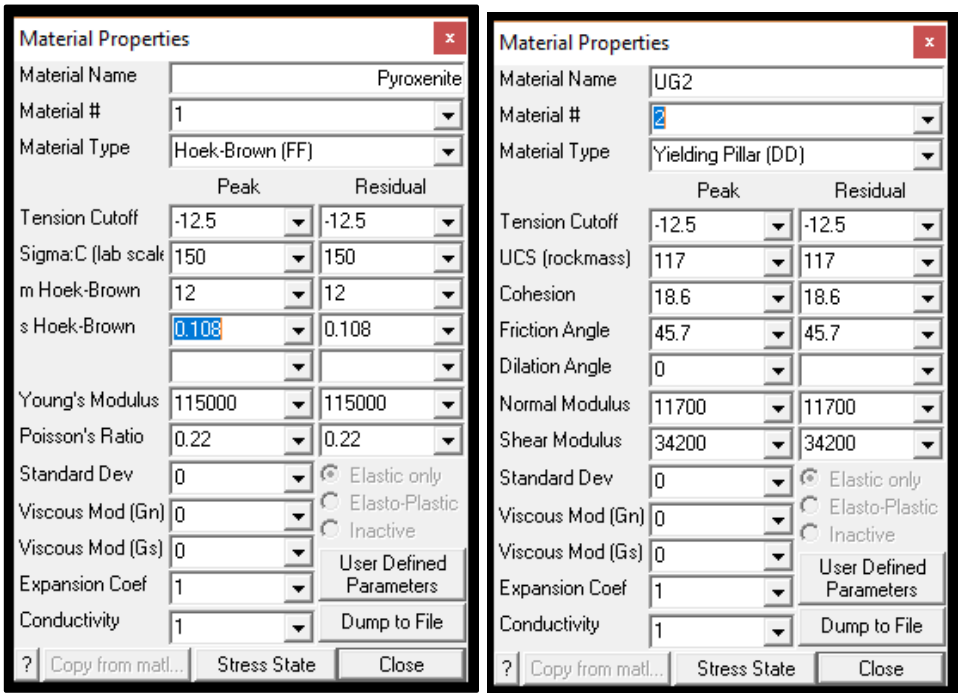


Figure 79: The input parameters used for the MAP3D numerical modelling of 14-23W crosscut

Table 3 indicates the criteria used in the MAP3D model and the possible variabilities which must be taken into consideration.

Table 3: Assumed parameters used in the model versus actual values

Assumed parameter	Assumed Parameter/description for the model	Actual values
UCS	UG2 Reef = 117 MPa Host rock = 150 MPa	56% of UCS value as determined from long term uniaxial compressive strength results. (Nyungu and Stacey, 2014).
K ratio	1.2 from Amandelbult empirical data	This varies due to the multi-reef mining characteristics and effects of the Merensky Reef remnants on UG2 Reef.
Surface topography	Flat (no variation over distance)	Varying topography (granite monoliths in surrounding areas)
Geology	Effects of different types of discontinuities within rock and the orientations of joints Geology was considered in the models and s parameters calculated for the Hoek Brown criteria. The rolling reef in the raiseline was considered.	Geology varies over the area considered due to the presence of the major faults (Trainsmash fault on western side).
Stoping width	1.5 m (UG2 Reef)	This may be larger or smaller due to the best cut variation from the sampling department and over break and under break of the hangingwall/footwall.
The rockmass state	Homogenous, continuous, and isotropic and intact.	Inhomogeneous and anisotropic. The rockmass was not a continuum but was comprised of a large number of blocks bound by discontinuities of which the size, shape, orientation, location and number of these blocks were mostly unknown.
Blast damage	Considered in the RCF calculation, not in MAP3D.	Difficult to quantify but may reduce pillar stability and strength.

Pillar behaviour	Spalling, scaling, influence of pillar loading conditions, time-dependent effects Hoek - Brown criteria was used.	The Hoek - Brown criteria was limited in that it assumed a rock was homogenous, isotropic, and intact.

5.1.5. Case Study 5: 14-20W excessive closure

At 14-20W UG2 panels and centre gully (Figure 79), a request to investigate a report of grout packs taking load and excessive timber elongates breaking was made. It was observed that the 0.8 m x 0.8 m Cemrite grout packs installed along the centre gully showed vertical cracks and crushing from unexpected high closure. This was unusual, as the 14-20W panels were not close to being completely mined out. The rate of closure was expected to be minimal as there was a reduced span between unmined areas and the area was not deep in comparison to the other higher closure panels (714.7 m below surface). Further investigation into the panels showed UG2 dynamic pillar failure at 14-20W 4E panel. Excessive closure close to the face and support failure was observed at 14-20W 4W panel.

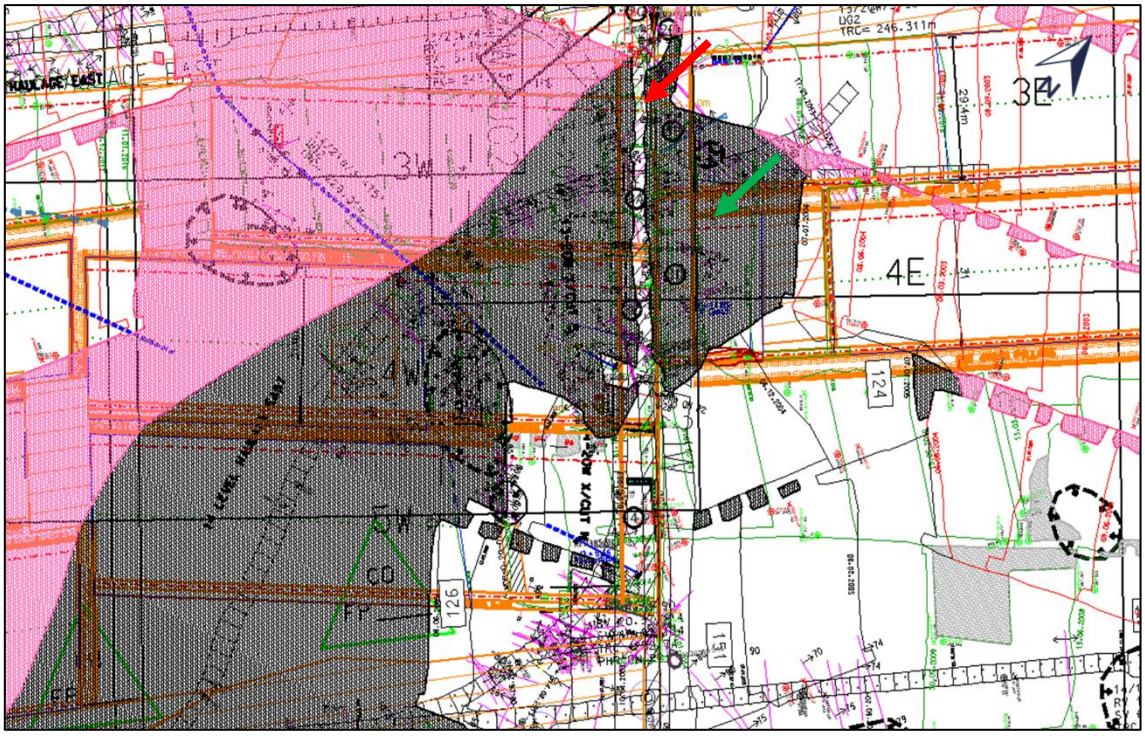


Figure 80: Plan showing the Merensky Reef remnant (black was off - reef and pink was - on reef projections) over UG2 panels. The red arrow indicates the centre gully of 14-20W, and the green arrow indicates the 4E in-stope pillar which dynamically failed

The west side of 14-20W and the east side of 14-21W were under higher stresses due to mining under a large Merensky Reef remnant. This remnant was 248 m long and 91 m wide at the narrowest point. The area was surrounded by both highly extracted UG2 Reef and Merensky Reef Mining (Figure 80).

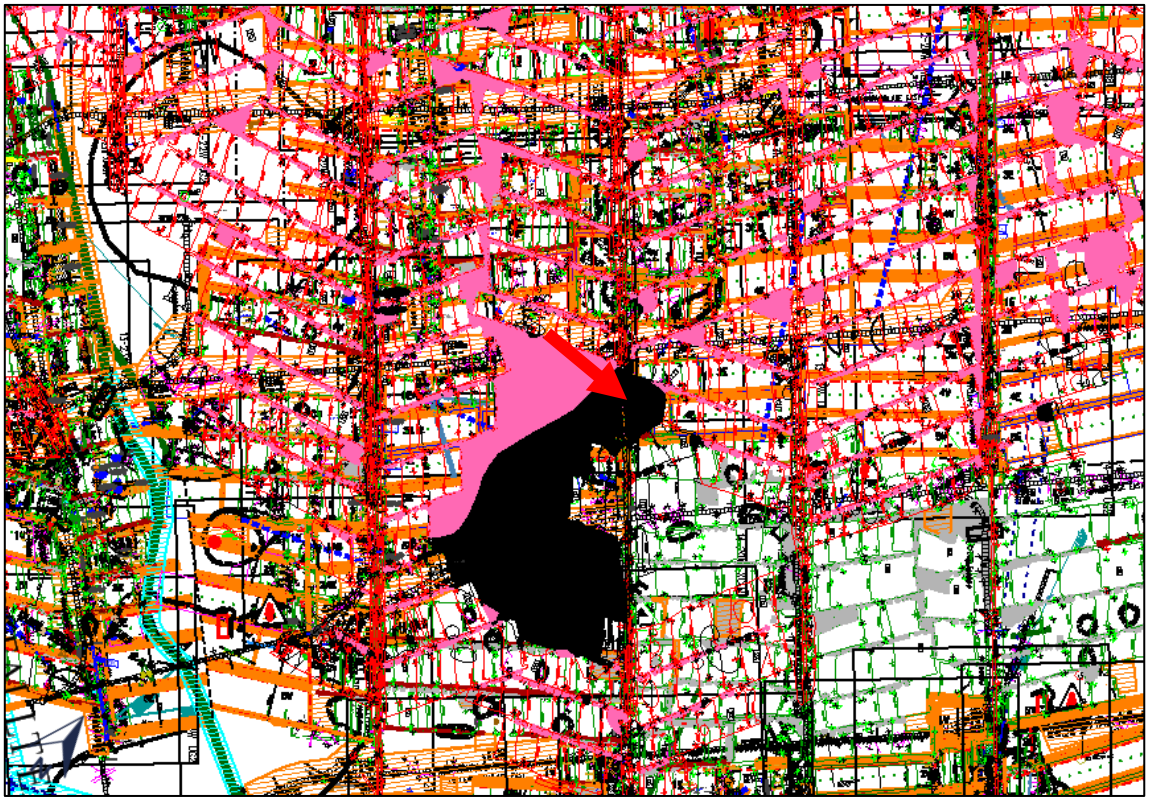


Figure 81: The location of 14-20W raiseline (red arrow) within the Merensky remnant (pink and black area)

5.1.5.1. Underground observations

5.1.5.1.1. 14-20W 4E panel

Possible dynamic failure of an in-stope pillar, approximately 10 m from the face, was observed at 14-20W 4E panel (Figure 81). This portion of the panel was under the Merensky Reef abutment and was approximately 20 m from the edge. Pillar rock could be seen approximately 7 m from the source pillar and the timber elongates at the edge of the pillar had reef embedded in them and marks from a high energy rock burst. The pillar was highly fractured on the one extremity, which resembles rock bursts observed in previously visited UG2 Reef panels such as 12-21W 4E UG2 panel (Figure 79).



Figure 82: The 14-20W 4E panel showing pillar remnants in the panel and the marks on the timber elongates

This pillar was not oversized and was fully on-reef, thus suggesting that the rate of closure influenced the increased stress in the pillar and did not allow the pillar to release the stress by means of fracturing on the pillar extremities. Instead the stress was released dynamically. If the local mine stiffness was high in comparison to the post peak stiffness of the pillar, dynamic failure would not occur as energy was absorbed by rock fracturing in the pillar (Maybee, 2000). This indicates a soft system at Tumela 1 shaft.

IMS Vantage modelling showed that the area was not expected to be highly stressed (Figure 82). The induced stresses on an area were expected to be 25-50 MPa so scaling was expected but not to the extent which was observed underground.

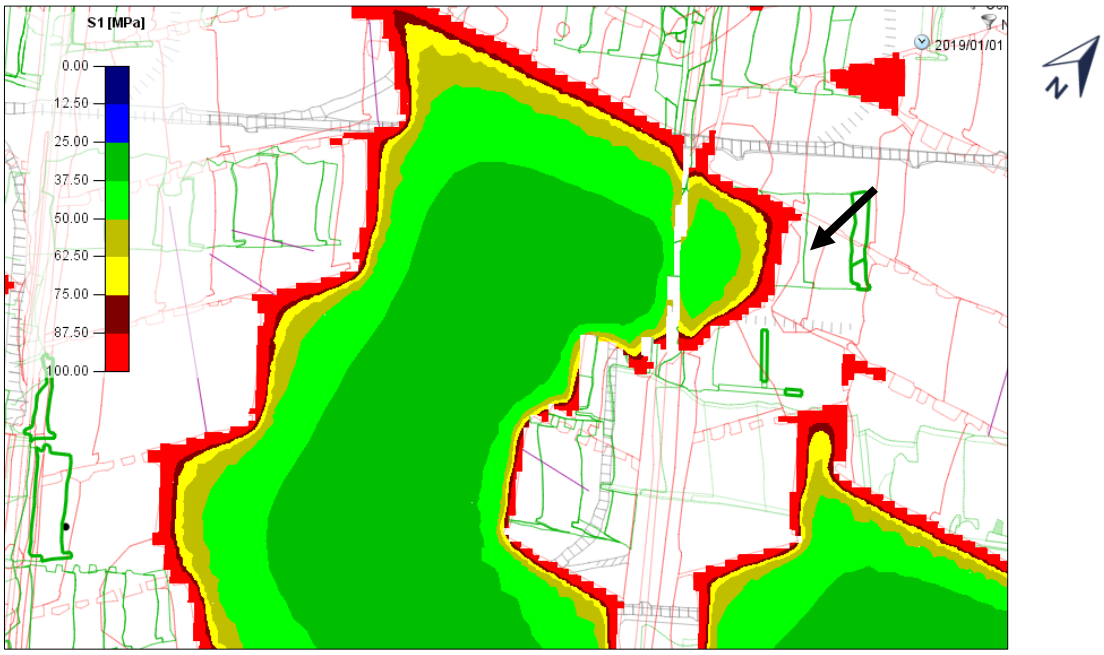


Figure 83: Stress modelled on Merensky Reef pillars i.e. stresses induced on the UG2 Reef by Merensky Reef remnant. Black Arrow indicates the dynamically failed in-stope pillar at 14-20W 4E

5.1.5.1.2. 14-20W 4W panel

The 14-20W 4W panel face was scaling excessively after it was not blasted for one day. The crew reported that drill steels were becoming embedded in the panel face. The drilling problems indicated high face stresses causing stress fractures ahead of the face and the lateral movement of shear ahead of the face.

The top pillar was scaling 5.0 m from the face, which was usually expected approximately 15 m away from the face. Timber elongates in the back area were observed to be failing and grout packs were taking load. A triggered rock movement monitoring device (RockSpy) in the travelling way (approximately 20 m from current face position) was observed. This unit monitors 1.5 m of immediate hangingwall. A triggered unit showed parting in the hangingwall.

This panel was stopped, and a regional pillar was left for additional control of the stress and closure in the area.

5.1.5.1.3. 14-20W Centre gully

The grout packs on the shoulders of the 14-20W centre gully were observed to be taking excessive load and had reached peak strength. This was seen by vertical cracks in the grout packs (Figure 83). In addition, the footwall below the grout packs on the shoulder of the centre gully had been failing under this excessive load. This had resulted in the grout packs becoming unstable and there was an increased risk of these grout packs falling into the centre gully. This had caused a fatal in other mines in the past. Due to the footwall become loose under the grout packs, the grout packs were not providing the required support resistance for the centre gully (Figure 84). No tensile cracks in the hangingwall of the centre gully were observed, but due to the high rate of closure and little support resistance (as the grout packs were unable to sustain load), the formation of tensile cracks was expected to occur more frequently. The 14-20W centre gully requires rehabilitation with cable anchors and new grout packs.

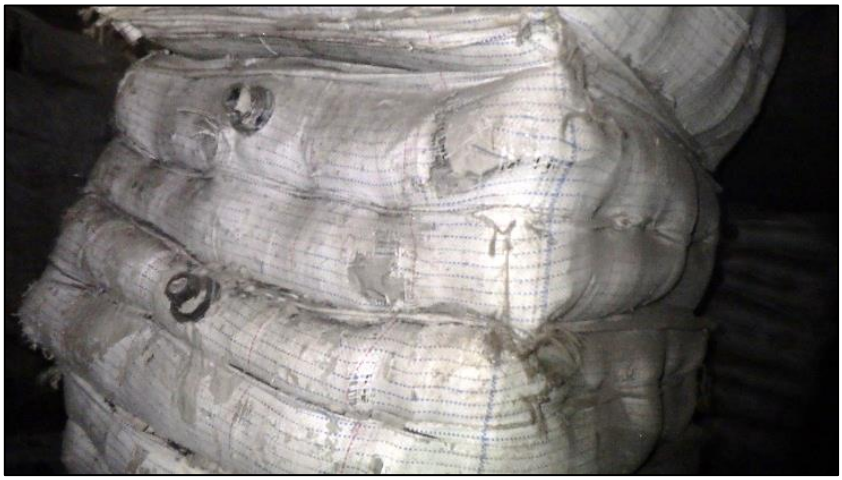


Figure 84: Damaged pack in centre gully



Figure 85: Damaged pack in centre gully showing the footwall failure below the grout pack

5.1.5.2. 14-20W Expected deformation and anomalies

The elastic closure as determined by IMS Vantage modelling (Figure 85) indicates that maximum closure should not be more than 40-50 mm in the panel and 30-40 mm over the raiseline. The Cemrite 0.8 m x 0.8 m grout packs maximum deformation at peak load was approximately 61 mm at 2100 kN. The grout packs had crushed considerably to near failure indicating closure of more than 100 mm over the centre gully. This was collaborated by rough closure measurements from failed timber elongates in the vicinity of these grout packs.

No prominent geological structures were observed in this centre gully, which eliminated the possibility of an unstable hangingwall block. Instead, as could be seen on plan, the raise on the Merensky Reef had split

the remnant over the raise. This smaller portion of the remnant was 44 m long and 30 m wide. Closure was seen where this remnant was, which may have concentrated stress over this area.

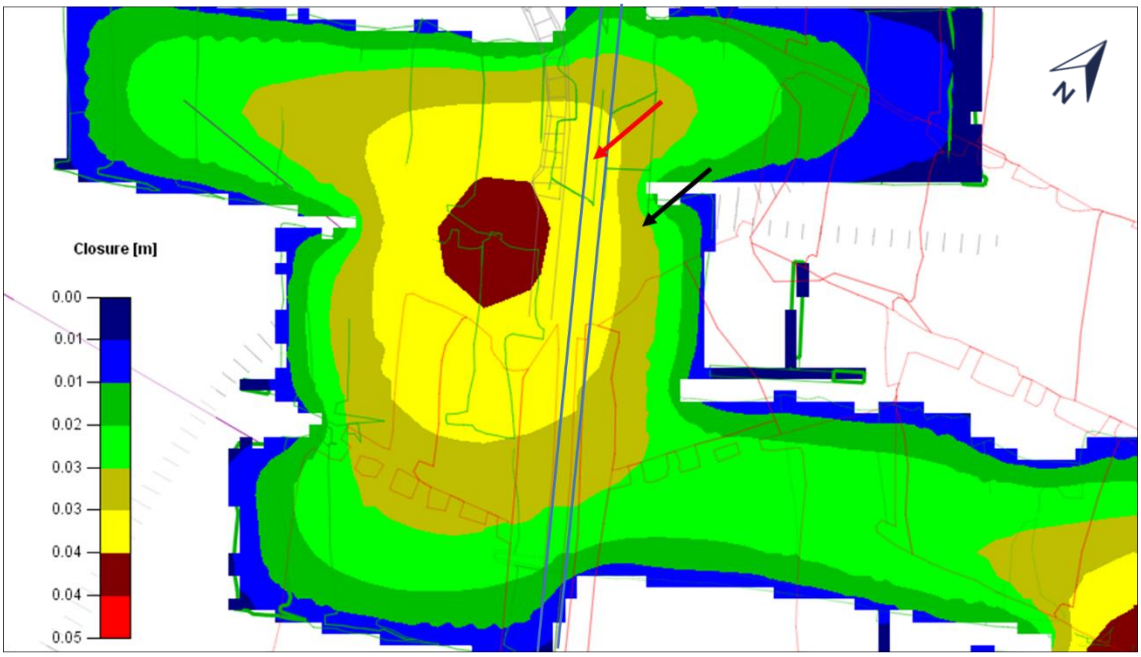


Figure 86: Expected closure at 14-20W panels (current state). The red arrow indicates the centre gully of 14-20W, and the black arrow indicates the 4E in-stope pillar which dynamically failed

Middling between the Merensky Reef and UG2 Reef was approximately 50 m, which was more than the average of the shaft (40 m) so induced stress and closure was expected to be less.

The stresses had probably increased even more due to the overall mining sequence being not conducted according to a proper layout for higher stressed areas (underhand configuration or “Christmas tree”, Figure 86). With the larger Merensky Reef pillars at the 17W, 16W, 15W and 14W raiselines having recently failed (as seen by large recorded seismic events), this had potentially put even more stress on this large Merensky Reef remnant area, which may had resulted in higher closure rates.

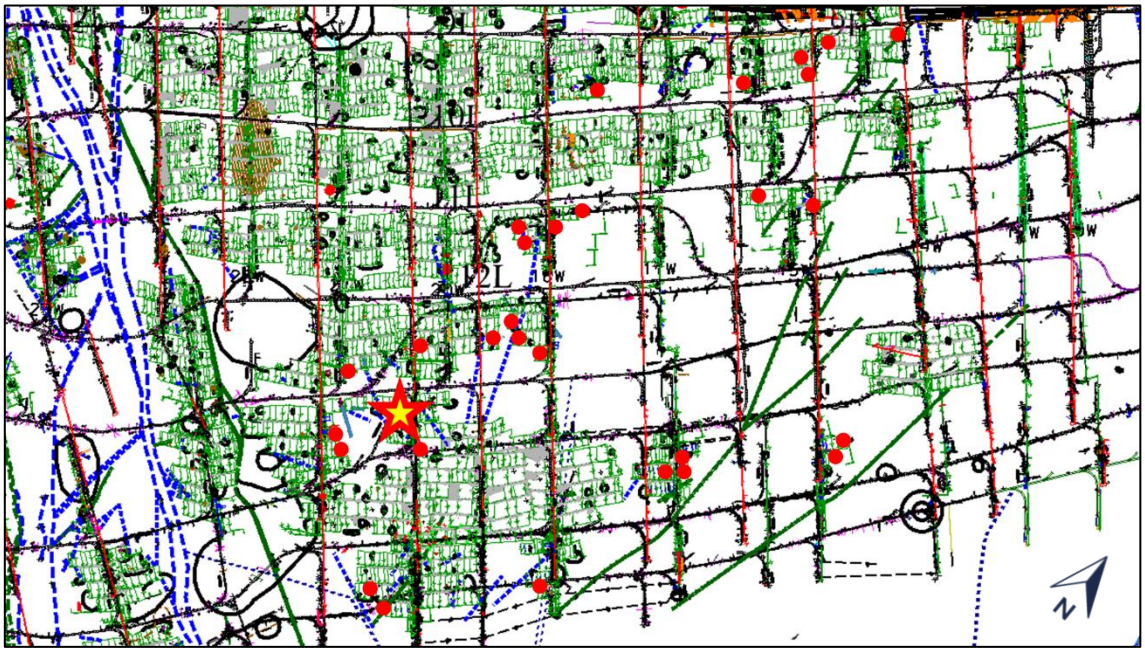


Figure 87: Plan showing the panels mined out and the position of 14-20W (red star) in relation to other mining panels

5.1.5.2.1. 14-20W recommendations

Underground observations made at 14-20W UG2 centre gully and panels, in comparison with the IMS Vantage stress and closure modelling, indicate there was a significant in - elastic component of closure at 14-20W. 10 m in the hangingwall of the UG2 Reef package was the P1 marker. If this P1 marker was detaching, this would explain the excess loading on the grout packs and the resultant failure of these packs. Further investigation would be done to determine if this marker had detached and was excessively loading the 14-20W raiseline.

To continue to mine 14-20W panels, the safety of the mining personnel travelling and working in this area had to be the primary consideration therefore, the full rehabilitation of 14-20W centre gully was required. An alternative travelling way was created, as to ensure people did not travel in the centre gully before rehabilitation takes place. 3.0 m cable anchors were installed to reinforce the beam and to cater for this wider area created when unstable grout packs were removed. Since the currently installed grout packs had failed or were supporting on residual strength, all current grout packs (from 2E ASG and below) had to have a new grout pack installed directly behind the original grout pack. Closure robots had been installed and visual monitoring of the new grout packs was being conducted to ensure they did not take additional load.

6. References

Bester, W.M. (2016). Tumela_TSD_BP 2017. Revision 2. Anglo American Platinum., Tumela Mine., Amandelbult Section.

Bureau of Indian Standards. (1973). Criteria for safety and design of structures subjected to underground blast. India. ISI Bull IS -6922, 1973.

Brink, A.v.Z., Hagan, T.O., Spottiswoode, S.M., Malan, D.F., Glazer, S.N., Lasocki, S. (2000a). Survey and Assessment of Techniques Used to Quantify the Potential for the rockmass Instability. CSIR: Division of Mining Technology. GAP 608.

Brink, A.v.Z., Hagan, T.O., Roberts, m.K.C., Milev, A. (2000b). Preliminary assessment of seismic hazard and risk in the Bushveld Complex platinum mines. The Safety in Mines Research Advisory Committee (SIMRAC) Report GAP 711. Department of Mineral and Energy Affairs, South Africa.

Brink, A.v.Z., Roberts, m.K.C., Spottiswoode, S.M. (2002). Further assessment of seismic hazard/risk in the Bushveld Complex platinum mines and the implication for regional and local support design. CSIR: Division of Mining Technology. GAP 821. Internal Document 2002-0268.

Cai, m. (2013). Principles of rock support in burst - prone ground. Tunnelling and Underground Space Technology 36 (2013) 46-56.

de Frey, F.S.A. (2002). Examine the criteria for establishing the small span small pillar concept as a safe mining method in deep mines. Mine Engineering Consultants CC. Research Enterprise at University of Pretoria (Pty) Ltd. GAP 828.

Drescher, K., Handley, m.F. (2003). Aspects of time-dependent deformation in hard rock at great depth. The South African Institute of Mining and Metallurgy, 2003.

Durrheim, R.J., Ogasawara, H. (2012). Can mine tremors be predicted? Observational studies of earthquake nucleation., triggering and rupture in South African mines. The Southern African Institute of Mining and Metallurgy. Southern Hemisphere International Rock Mechanics Symposium SHIRMS 2012.

Hertz, H. (1896). On the contact of rigid solids and on hardness. Miscellaneous Papers. Macmillan., London, UK.

Hoek, E., Brown, E.T. (1980). Underground Excavations in Rock. Institution of Mining and Metallurgy, London., 527p.

Jager, A.J., Ryder, J.A. (1999). A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines. The Safety in Mines Research Advisory Committee (SIMRAC). Johannesburg 370 pages.

Joughin, W.C. (2011). Risk in Rock Engineering design. In: Proceedings of Rock Engineering for Managers in Hard Rock Tabular Mines 2011, Johannesburg, 1-2 June 2011. The Southern African Institute of Mining and Metallurgy. pp. 121-160.

Kaiser, P.K., Tannant, D.D., McCreath, D.R. (1996). Canadian Rockburst Support Handbook. Geomechanics Research Centre, Laurentian University, Sudbury, Ontario. 314p.

Kaiser, P K., Kim, B., Bewick, R.P., Valley, B. (2010). The rockmass strength at depth and implications for pillar design. Transactions of the Institutions of Mining and Metallurgy: Section A Volume 120. 2011- Issue 3.

Kaiser, P.K., Cai, m. (2012). Design of rock support system under rockburst condition. Journal of rock mechanics and Geotechnical Engineering. 2012, 4 (3): 215-227.

Kaiser, P.K. Cai, m. (2013). Critical review of design principles for rock support in burst - prone ground - time to rethink! Bharti School of Engineering, Laurentian University, Canada.

Kwiatek, G., Ben - Zion, Y. (2013). Assessment of P and S wave energy radiated from very small shear - tensile seismic events in a deep South African mine. Journal of Geophysics. Res. Solid Earth. 118, 3630-3641.

Leach, A.R., Naidoo, K., Balt, K.D., Rangasamy, T., Spencer, D. (2002). Survey and assessment of support for non - standard (anomalous) stope areas in the gold and platinum industry. Research agency: Itasca Africa (Pty) Ltd. Research report number: GAP 607.

Lenhardt, W.A. (1988). Damage studies at deep level African gold mine. Proceedings of the 2nd International Symposium on “Rockburst and seismicity in mines”, Minnesota., USA, 1988.

Malan, D.F., Vogler, U.W., Drescher, K. (1997). Time-dependent behaviour of hard rock in deep level gold mines. CSIR Division of Mining Technology. The South African Institute of Mining and Metallurgy.

Malan, D.F. (2000). Guidelines for measuring and analysing continuous stope closure behaviour in deep tabular excavations. The Safety in Mines Research Advisory Committee (SIMRAC).

Martin, C.D., Kaiser, P.K. McCreath, D.R. (1999). Hoek - Brown parameters for predicting the depth of brittle failure around tunnels. Canadian Geotechnical Journal., Vol. 36(1), pp. 136-151.

Maritz, J.A. (2015). The effect of shear stresses on pillar strength. Magister Engineering (Mining Engineering). Department of Mining Engineering. University of Pretoria.

Maybee, W.G. (2000). Pillar design in hard brittle rocks. Ph. D Thesis. School of Graduate Studies., Laurentian University, Sudbury, Ontario, Canada.

Miovsky, P., Scheepers, J. (2007). Seismicity in the Bushveld - Problems Experienced at Impala Platinum Mines Limited No. 10 Shaft (South Africa). Geoscience Engineering Volume Liii (2007), No.1, P. 1-14, Issn 1802-5420.

Moganedi, K.A., Stacey, T.R. (2019). Value creation as an approach to the management and control of rockburst damage in tunnels. Tunnelling and Underground Space Technology 83 (2019) 545-551.

MTR Corporation Limited Consultancy Agreement. (2009). No. NEX/2102 Express Rail Link Preliminary Design for XRL Tunnels & Associated Structures Working Paper No. 44. Structural Condition Survey for EIA Research at Lai Chi Kok Hospital.

Naidoo, K., Handley, m.F. (1998). Basic principles for stable gullies in the gold and platinum mines of South Africa. The Journal of the South African Institute of Mining and Metallurgy.

Nyungu, D. (2013). Effect of time on the tensile strength of several bushveld complex rock types. University of Witwatersrand., Johannesburg., South Africa.

Nyungu, D. Stacey, T.R. (2014). Time-dependent tensile strengths of Bushveld Complex rocks and implications for rock failure around mining excavations. The Southern African Institute of Mining and Metallurgy. Vol.114 n.10 Johannesburg Oct 2014.

Ortlepp, W. D. (1997). Rock Fracture and Rockbursts, an illustrative research. The South African Institute of Mining and Metallurgy.

Persson, P. A. (1978). The Basic Mechanisms in Rock Blasting. Proc. 2. International Congress on Rock Mechanics. Vol. 111b. Belgrade. 1978.

Prandtl, L. (1921). Zeit. Angew. Math. Mech. Vol.1. No.1. pp. 15-20.

Pretorius, m.J. (2005) Managing the risk once the risk profile has been established. Proceedings 3rd Southern African Rock Engineering Symposium (SARES2005), SAIMM Symposium Series S41, pp. 335-343.

Riemer, K.L., Durrheim, R.J. (2011). Mining Seismicity in the Witwatersrand Basin: Monitoring, Mechanisms and Mitigation Strategies in Perspective. Journal of Rock Mechanics and Geotechnical Engineering. 2011, 3 (3): 250-259.

Richardson, A., Agapito, J.F.T., Gilbride, L. (1999). Rock mechanics issues in the Trona Patch. In: Proceedings of the 18th International Conference on Ground Control in Mining. Morgantown, West Virginia. p. 194-201, 1999.

Singh, N., Urcan, H., Naidoo, K., Ryder, J., Watson, B.P., Milev, A.M., Roberts, m.K.C. (2005). The influence of pillars on the Merensky Reef horizon on stoping operations on the underlying UG2 Reef horizon. The South African Institute of Mining and Metallurgy.

Siskind, D.E. (2000). Vibrations from blasting. International Society of Explosive Engineers (2000). p. 120.

Spottiswoode, S. (2009). Mine seismicity: prediction or forecasting? The Southern African Institute of Mining and Metallurgy hard rock safe Safety Conference 2009. Page 81.

Stacey, T. R. (1981). A Simple Extension Strain Criterion for Fracture of Brittle Rock. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 18, Pp. 469-474.

Stacey, T. R., Page, C. H. (1986). Practical handbook for underground rock mechanics. Clausthal - Zellerfeld., West Germany. Trans tech publications. 144 p.

Stacey, T. R. (2019). Email communication -30 January 2019.

Szwedzicki, T. (2003). The rockmass behaviour prior to failure. International journal of rock mechanics and mineral sciences., 40. 573-584.

Urcan, H., Naidoo, K., Ryder, J., Watson, B.P., Milev, A.M., Jager, T., Spootiswoode, S., Grave, m., Roberts, m.K.C. (2004). Strategies for the mining of the UG2 Reef below partially extracted Merensky Reef. CSIR Mining Technology. 3.1. Miningtek report number: 2004-0197.

van Aswegen, G., Hobson, S. (2017). Research report Tumela Pillars. IMS Document Number: AM1- REP -20171124- GvAv.

Vardar, O., Tahmasebinia, F., Zhang, C., Canbulat, I., Saydam, S. (2017). A Review of Uncontrolled Pillar Failures. Procedia Engineering 191 (2017) 631-637 Symposium of the International Society for Rock Mechanics.

Vieira, F.M.C.C., Durrheim, R.J. (2005). Design and support of rockpasses at ultra - deep levels. The South African Institute of Mining and Metallurgy.

Villaescusa, E., Kusuia, A., Drovera, C. (2016). Ground Support Design for Sudden and Violent Failures in Hard Rock Tunnels. Western Australian School of Mines - Curtin University of Technology. CRC Mining. Locked Bag 30. Kalgoorlie, WA, 6430 Australia.

Viljoen, m.J., Theron, J., Underwood, B., Walters, B.M., Weaver, J. and Peyerl, W. (1986). The Amandelbult Section of Rustenburg Platinum Mines Limited, with reference to the Merensky Reef. In. Anhaeusser., C.R. and Maske., S. (Eds). Mineral Deposits of Southern Africa. Geological Society of South Africa Johannesburg, South Africa. II. 1041-1060.

Watson, B.P., Roberts, m.K.C., Nkwana, m.M., Kuijpers, J., van Aswegen, L. (2006). The stress - strain behaviour of in-stope pillars in the Bushveld Platinum deposits in South Africa. The Southern African Institute of Mining and Metallurgy.

Watson, B.P., Ryder, J.A., Kataka, m.O., Kuijpers, J.S., Leteane, F.P. (2008). Merensky Pillar Strength Formulae Based on Back - Analysis of Pillar Failures at Impala Platinum. The Southern African Institute of Mining and Metallurgy. Vol. 108. 2008. Pp. 449-461.

Watson, B.P. (2010). Rock behaviour of the bushveld Merensky Reef and the design of in-stope pillars. ISRM Secretary General. In consideration for the Rocha Medal. November 2010.

Watson, B.P., Kuijpers, J.S., Stacey, T.R. (2010). Design of Merensky Reef crush pillars. The Southern African Institute of Mining and Metallurgy. 2010. Paper received Jul. 2010; revised paper received Sep. 2010.

York, G., Canbulat, I., Jack, B. (2000). Coal pillar design procedures. COL 337. The Safety in Mines Research Advisory Committee (SIMRAC).

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