The influence of pillars on the Merensky Reef horizon on stoping operations on the underlying UG2 Reef horizon


Introduction

Extensive UG2 Reef reserves underlie the partially mined Merensky Reef (MR) within the Bushveld Complex. The middling between the two reef horizons varies from 4 m to 400 m. Unmined ground in the form of pillars, potholes and remnants has been left during the mining of the MR horizon. The adverse influence of the unmined portion of MR horizon has become a major concern when mining on the UG2 Reef horizon. This paper quantifies the influence of partially extracted Merensky Reef on mining of the UG2 Reef, and aims to provide recommendations for mining strategies, as well as regional and local support to achieve efficient and safe extraction of the UG2 Reef, for various middlings beneath the Merensky Reef horizon. In some cases it was found that relatively shallow UG2 Reef mining could encounter conditions similar to those experienced in deep and ultra-deep mining environments.

Evaluation of mining on the UG2 Reef

To clearly understand the issues affecting the mining of the UG2 stopes under the MR remnants, both underground testing and conceptual studies were undertaken. The former involved underground inspections together with a detailed instrumentation and monitoring programme. The conceptual studies revolved around literature studies and numerical modelling. The numerical modelling codes used for this assessment included MINSIM 2000, FLAC 2D and DIGS.

The size and shape of the MR remnants varied significantly and an analytical approach to determine a generic method of evaluating the effect of the overlying MR remnants on the stoping on the underlying UG2 Reef horizon was investigated (Urcan et al., 2004). MINSIM 2000, an elastic boundary element program, was used to study the stress regimes on the UG2 Reef horizon under the MR pillars. A series of circular, square and rectangular pillars with different dimensions were created on the MR horizon and modelled using MINSIM. In addition, the influence of k-ratio and dip angle were also studied.

The results of these conceptual models, shown in Figure 2, should be taken as a guide to estimate field stresses on the UG2 Reef in the vicinity of the MR remnants. Such a guide will be useful at mine planning meetings as it

Synopsis

Merensky Reef is mined extensively within the Bushveld Complex. In previously mined-out areas on the Merensky Reef horizon there are pillars, potholes and remnants that have not been mined. These unmined blocks of ground on the Merensky Reef horizon can influence the mining of the underlying UG2 Reef. The extent of the influence will depend on the size of unmined ground and the middling between the two reef horizons. This paper quantifies the influence of partially extracted Merensky Reef on mining of the UG2 Reef, and aims to provide recommendations for mining strategies, as well as regional and local support to achieve efficient and safe extraction of the UG2 Reef, for various middlings beneath the Merensky Reef horizon. In some cases it was found that relatively shallow UG2 Reef mining could encounter conditions similar to those experienced in deep and ultra-deep mining environments.
The influence of pillars on the Merensky Reef horizon on stoping operations would provide the rock engineering practioner with a tool to determine the possible stresses that would impact on the UG2 mining without undertaking protracted numerical modelling exercises. This should be used only as a first pass method and once there is agreement on the possibility of mining, a more detailed assessment must be undertaken prior to any mining.

The MR remnants were modelled as isolated pillars in a 980 m x 980 m area. Hence, these model results may be considered as the worst-case scenario. In actual mining layouts, there will be other remnants in the vicinity, which will share the overburden load, resulting in reduced stresses on the remnants. Average Pillar Stress (APS) for the modelled MR remnants for various sizes and depths is given in Table I.

To show the method of using Table I, an example of determining the first pass APS on an MR remnant is provided as follows: for a pillar of 20 m radius, at a depth of 600 m below surface, the APS is estimated to be 321 MPa.

The findings of the MINSIM 2000 modelling are as follows:

- The magnitudes of peak vertical field stress on the UG2 reef were not significantly influenced by shapes of the remnants, for remnants with similar areas
- \( k \)-ratios of 0.5 and 2.0 were used in the modelling and it was found that the influences of the different \( k \)-ratios are minimal on the vertical stress field acting on the UG2 Reef mining
- The effect of reef dip angles (10° and 20°) is minimal on the vertical field stress for UG2 Reef mining
- Depending on the size of the remnant and the middling between the Merensky and UG2 reefs, relatively shallow depth UG2 Reef mining under the MR remnants will experience conditions that are similar to deep and ultra-deep mining conditions.

Potential failure mechanisms when mining UG2 stopes under MR pillars

The ability to mine the UG2 Reef horizon safely and efficiently is determined by:

- Depth of mining
The size of the overlying MR pillar

The distance (middling) between the Merensky and UG2 reefs horizons.

Ground conditions for a stope mining on the UG2 Reef horizon at relatively shallow depth changes drastically, due to the increasing stress, as the stope face approaches the first edge of the overlying MR remnant. This remnant acts as a conduit for the principal stress and there is a concentration of stress ahead of the UG2 stope face. As the mining progresses beneath the pillar, this concentration of stress increases significantly. The increase in the stress concentrations continues until the UG2 stope has progressed beyond the far edge of the MR pillar. As a result of this increase in stress on the underlying UG2 stope, conditions change from a low-stress, shallow mining environment to a high-stress mining environment with conditions similar to those experienced at deep-level mining operations. Refer to Figure 3.

In order to study the UG2 Reef mining conditions under the MR remnants, numerical modelling of a series of scenarios was undertaken. Numerical modelling using MINSIM was undertaken on seven existing Merensky and UG2 reefs mining layouts. Under selected MR remnants, extraction on the UG2 Reef horizon was modelled. No in-panel pillars (generally crush pillars) were modelled for conceptual UG2 Reef mining. The middling between the MR remnants and UG2 Reef mining varied between 20 m and 38 m. Stoping widths of 1.5 m were assumed for the models. Elastic constants, i.e. Young’s modulus of 50 GPa and Poisson’s ratio of 0.2, were assumed.

Figure 4a represents the model results for three different remnants at a mining depth of approximately 1 450 m. The middling between the MR remnants and UG2 Reef mining varied between 20 m and 38 m. Stoping widths of 1.5 m were assumed for the models. Elastic constants, i.e. Young’s modulus of 50 GPa and Poisson’s ratio of 0.2, were assumed.

Figure 4a represents the model results for three different remnants at a mining depth of approximately 1 450 m. The middling between the MR remnants and UG2 Reef mining varied between 20 m and 38 m. Stoping widths of 1.5 m were assumed for the models. Elastic constants, i.e. Young’s modulus of 50 GPa and Poisson’s ratio of 0.2, were assumed.

To verify the change in the stresses acting ahead of the UG2 stope, a section line was drawn through all three areas of concern. For discussion purposes only, the face stresses for each of the conceptual UG2 mining steps, along section A-A’, is shown in Figure 4b. For comparison, a face stress profile that is equivalent to single reef mining in solid ground at a 1 550 m depth is also shown. In all cases, the UG2 Reef face stresses under the MR remnants are in the region of 300 MPa or higher. These values are almost double those that would be experienced by a stope on a single reef horizon mining in solid ground at a 1 550 m depth. When UG2 Reef mining is outside the area of influence of the MR remnant, the stoping occurs in a destressed environment and face stresses are equivalent to those experienced at very shallow depths. Similar findings were achieved from other models that were analysed. One of the most significant findings was that the middling between the two reef horizons is the most influential in determining the magnitude of the stress acting ahead of the underlying UG2 stope horizon.

In the course of MINSIM modelling of multi-reef mining scenarios as mentioned above, it was noted that the modelled vertical stresses were high, as expected. The horizontal stress results within the immediate hangingwall of the UG2 Reef mining, for the 20 m middling, indicated that the once the UG2 Reef mining is within the abutment zone of the MR

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Figure 4a and 4b—Conceptual modelling and associated results

Figure 5—Horizontal stress results for 20 m middling; mining depth = 1450 m

Figure 6—Geometry modelled using DIGS

remnant, the horizontal stresses were highly compressive on and ahead of the face. These stresses become tensile with magnitudes of up to 200 MPa (tensile) in the mined-out areas as shown in Figure 5.

This situation appeared to be implausible and the possibility of some form of modelling or program error was mooted. Confirmatory modelling exercise using the 2D DIGS4 program was undertaken, using the geometry shown in Figure 6. Stages of UG2 Reef mining were then modelled, starting from the 200 m position shown in Figure 6 and progressing to a final face position of 260 m (ultimate span of 60 m).

In the above model, the following inputs were used:

- middling of 20 m
- \( E = 80 \) GPa
- \( v = 0.2 \)
- \( \sigma_{v} = 45 \) MPa (depth = 1500m), \( \sigma_{h} = 45 \) MPa (k = 1)
- grid sizes: MR = 2 m, UG2 = 1 m.

The analytic APS on the 20 m MR remnant, prior to UG2 reef stoping, was calculated to be 396 MPa. Figure 7a shows that only a relatively small amount of destressing occurred on the MR remnant as stoping progressed towards the centre of the overlying remnant. The
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modelling results, however, showed that the elastic convergence in the UG2 Reef stope accelerated sharply. Shown in Figure 7b are the plots of the variation of horizontal (skin) stresses in the hangingwall of the UG2 Reef model as stoping progresses. The same high tensile stresses are present in this model as in the MINSIM models discussed earlier. This modelling served to demonstrate the very likely presence of tensile horizontal skin stresses. Presented by Ryder (2005)6

The following technical argument can be used to describe the mechanism of the origin of the high horizontal tensile stresses. The induced horizontal stress on the reef horizon (due to stope convergence in elastic ground) is the same as the induced vertical stress. For example, when stoping on a single horizon, the induced vertical stress must equal minus the field stress of $\sigma_n$ and so the induced horizontal (skin) stress is also $-\sigma_n$, which means the absolute horizontal stress is small and compressive once the field horizontal stress $\sigma_h$ is added back (provided $k>1$).

When stoping a second reef in fully destressed ground, the field stresses are low and compressive, and so the induced horizontal stress is low and tensile, giving a net absolute horizontal stress likely to be low and compressive. Once the second reef transgresses into the rockmass where the field vertical stress is high, however, large tensile horizontal stresses will be induced and the likely field horizontal compressive stress is unable to offset this large level of tensile stress.

Apart from complications due to interaction between the two reefs (possibly fairly small, judging from the APS curve of Figure 7a), it is proposed that the further increase of horizontal skin tension is ascribable to shear-induced ride on the UG2 Reef mined in the vicinity of the remnant. The stresses illustrated in Figure 7b are in the hangingwall skin of the UG2 Reef, but further examination of the DIGS results showed that the horizontal tension persisted typically 3 m to 8 m up into the hangingwall. In an even larger zone, more than 10 m into the hangingwall, substantial tensile vertical stresses greater than 5 MPa were also present.

This combination of high elastic convergences, very high horizontal tensile stresses (able to rupture even the strongest intact rocks) and significant vertical tensions (able to rupture strong parting planes) is highly unfavourable for hangingwall stability. Observations from underground conditions found increasingly blocky and unstable hangingwall conditions as stoping approaches and transgresses a strong stress shadow in a low middling situation, which confirms these conclusions. Figure 8 shows some of the conditions observed when the UG2 stoping is close to the abutment of the overlying MR faces.

Implications for support design are considerable, especially once the UG2 stoping face reaches the edge of the destressing shadow, as shown in Figure 9. Substantial upgraded support systems become necessary, with both high areal coverage and the ability to accommodate high closure, when stoping operations are being carried out in the high abutment stress zone. In the modelled environment, the required support resistance appears to be such as to support at least 10 m of rock, that is, about 300 kPa. Suitable support types would be, for example, backfill with supplementary stiff elongates, or appropriately designed grout packs at close spacing.

The poor UG2 hangingwall conditions encountered underground when mining under an MR remnant appear to be worse than those that might be expected as a result of the high levels of vertical stress. In fact, strong induced tensile stresses (which are not normally encountered in ultra-deep single-reef mining) are likely to lead to poor hangingwall conditions, with upgraded support requirements. From the two scenarios investigated (20 m middling vs. 38 m middling), it was observed that the horizontal stresses have high magnitudes in both compression and tension. It is

![Image of graphs showing field stresses, APS on remnant, and horizontal skin stresses](image-url)
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suggested that the middling has a significant influence on this aspect of the stress regime acting on the UG2 Reef horizon. Further work is clearly required to confirm and delimit these conclusions.

Underground monitoring programme

Continuous closure monitoring was conducted at two sites at a deep platinum mine in the Western Bushveld to obtain an understanding and a comparison between ground behaviour in destressed conditions and conditions when mining under a remnant. It was also the intention to compare measurements of closure with convergence data obtained from numerical modelling reported in the earlier section of this report. Two different sites were monitored:

- Mining the UG2 reef under MR remnant conditions;
- MR virgin ground conditions. This site was chosen to compare the values obtained for mining operations under virgin conditions.

Telescopic closure meters, developed by the CSIR, were installed in the panels to monitor the closure in the area. Peak velocity detectors (PVDs) were installed adjacent to each closure meter in order to obtain information on peak particle velocities (PPVs) that could result from seismic events under normal and high stress conditions. Figures 10a and 10b show the two types of instrumentation units that were developed by the CSIR and installed in the stope.

A useful closure parameter is the closure ratio (CR). For a single mining increment \( j \), CR is defined as the ratio of instantaneous to total daily closure. Calculation of CR is demonstrated in Figure 11 after Malan (2003).

From previous monitoring and analysis of closure rates, it has been observed that there is a good correlation between instantaneous closure and PPV data. In all the areas monitored, PPV instruments were installed in the panel; however, not all instruments successfully recorded data due problems encountered underground. Malan and Napier (1999) found that closure ratios were a good indicator of geotechnical conditions. From underground observations it was noted that low closure ratio values were typically associated with poor hangingwall conditions and a high risk of falls of ground, whereas high closure ratios were associated with areas prone to face bursting on the deep-level gold mines. A plan of the area monitored is presented in Figure 12. The stope that was investigated was at a depth of 1 556 m with a 20 m middling separating the UG2 and Merensky reefs.
The closure meters were initially placed 1 m apart as mining advanced to obtain maximum data input. An interpretation of the data shows that the maximum deformation occurs during blasting time. The closure behaviour of the UG2 Reef is characterized by a small instantaneous jump after blasting, followed by a low steady-state closure rate. The circles, in Figure 13, show the stope production blasts. The average closure rate is 3 mm per day. The average closure ratio calculated for this stope was 0.36. The closure profiles from different positions within the stope showed similar patterns. The closure profile for the UG2 Reef panel is shown in Figure 13.

Monitoring in the panel was stopped when the panel was subjected to strong ground motion from a seismic event, resulting in a fall of ground. The average closure ratio of 0.35 obtained from the UG2 Reef mining under a MR remnant pillar is similar to those obtained by Malan (2003) on the study undertaken on the Carbon Leader Reef, in seismically active areas within deep-level gold mines. Further work is required to confirm this initial conclusion.

Underground seismic measurements were carried out at a number of different positions within the stope. However, due to the difficult underground conditions and high humidity, most of the PVDs were damaged or lost. Two data-sets were available for analysis. The first one contained 484 seismic events with a maximum PPV of 2.4 m/s, recorded over a period of 7 days. The second contained a limited number of 6 events with a maximum PPV of 0.13 m/s, recorded over a period of 5 days.

Case studies

In order to evaluate the conditions of the UG2 Reef mining under the MR remnants, various sites were visited. These sites were then modelled, using MINSIM 2000, to study the stress regimes and convergence levels on the UG2 Reef mining. This was an attempt to link observed conditions to the numerical modelling. An example of one such case study is discussed below.

Investigations were carried out in January 2004, in a stope approximately 1 500 m below surface. The middling between the UG2 and Merensky reefs was 20 m. The mining on Panel 4E extended halfway across the MR remnant after Panel 4E had mined across the top segment of the remnant, as shown in Figure 14.
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Modelling results for Panel 4E are presented in Figure 15a and 15b. Prior to any UG2 reef mining in this area, the vertical field stress under the MR remnant is approximately 120 MPa on UG2 Reef elevation. In June 2002 the face position of the UG2 Reef was 12 m behind the MR remnant and lagging 26 m behind Panel 5E, the face stress was 130 MPa. In September 2002 no mining took place at Panel 4E. Panel 5E was advanced by 54 m, resulting in Panel 4E lagging 80 m behind Panel 5E. At this stage face stresses in Panel 4E increased to 160 MPa. In December 2002, Panel 4E was directly under the middle of the Merensky Reef remnant. At this position Panel 4E lagged behind the Panel 5E by 64 m and the face stress increased to 370 MPa. The results shown in Figure 15b highlight the considerable increase in convergence under and ahead of the MR remnant. The maximum convergence under the remnant is 95 mm.

Severely fractured face and evidence of fall of ground is shown in Figure 16a. This photograph was taken immediately down-dip of Pillar 4 looking towards Panel 4E face. High closure and hangingwall fracturing was present under the Merensky Reef remnant and is shown in Figure 16b. Pillar 2 showed minor fracturing, as shown in Figure 16c. The pillar was 4 m behind the Merensky Reef remnant and the size of the pillar was 4 m and 2 m wide on west and east sides, respectively, with a length of 6.5 m. This pillar was ledged (carried a siding) approximately 0.5 m to 1 m from west to east. Figure 16d shows severe scaling that was present on the down-dip side of Pillar 4. This pillar was sited immediately under the MR remnant without a siding.

The numerical modelling for the eastern panels indicated that the MR abutment edge exerted a stress of 120 MPa on the UG2 Reef elevation (prior to UG2 Reef mining in the vicinity of the remnant). These edge stresses indicate that the conditions may be similar to those at ultra-deep-level mining with an added hazard of the high horizontal tensile stresses described earlier adding to potential hangingwall instability.

Conclusions

The study on the MR remnant shapes and sizes (including potholes, regional pillars, etc.) from the various platinum mines revealed that the remnant sizes ranged from 16 m² to 96 000 m² with an average area of 6 400 m². Cumulative frequency analysis indicated that 90% of the remnants studied were less than 17 000 m² in size with 50% being less than 2 000 m² in size.

MINSIM 2000 studies indicated relatively shallow depth UG2 reef mining under the Merensky Reef remnants can experience conditions that are similar to deep and ultra-deep
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Figure 14—Locality plans of pillar on Merensky Reef horizon (in dashed outline)

Figure 15—MinSim model results for Panel 4E
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mining conditions. This finding is dependent on the size of the MR pillar as well as the middling between the two reef horizons.

Conceptual MINSIM studies indicated the presence of high horizontal stresses (compressive and tensile) in the hangingwall of the UG2 stope when mining within the abutment zone of the MR remnant. Numerical modelling of the hangingwall skin of the UG2 Reef using DIGS showed that the horizontal tension persisted typically 3 m to 8 m up into the hangingwall. In an even larger zone, more than 10 m into the hangingwall, substantial tensile vertical stresses in excess of 5 MPa were noted.

A closure ratio of 1 was obtained from the MR panels. This value of 1 implies that the rockmass is showing true elastic behaviour. The average closure ratio is 0.35 in UG2 reef stope panels that mined into the high abutment stress zone caused by the overlying MR remnants. A closure ratio of 0.36 is typical for the Carbon Leader Reef, which is found in deep-level gold mines. It can be argued that, when mining under the overlying pillars, the conditions experienced will be similar to those of mining at depth. Further work will be needed to validate this conclusion.

From underground observations, it is considered that the 45° rule is applicable for estimating the zone of MR remnant stress concentration. In the proximity of these remnants differential and time dependent movement occurs in the UG2 Reef hangingwall between blocks constituting the jointed and at times fractured hangingwall. Stress-induced deformation of the rockmass by mobilizing joint-bounded blocks appears to be the preferred method of stress relaxation in the stope face rather than fracturing in the hangingwall.

When UG2 staking operations are within the abutment stress zone from the overlying MR remnant, the support system will have to be changed so that it can cater for large hangingwall and footwall deformations while maintaining the hangingwall integrity using support units that provide areal coverage. One such example would be backfill.

Within the zone of MR remnant stress concentration (45° rule) UG2 Reef in-stope pillar size is also critical. Oversize pillars result in high pillar stresses prior to failure, which can be violent. The consequence of this can be pillar punching and associated hangingwall damage.

Acknowledgements

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