SUBLEVEL OPEN STOPING AT DEPTH ON TARGET MINE

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SYNOPSIS

With improved geological and geotechnical information available, the current mining challenges, ventilation constraints, the trackless development to "open-up" the Target Mine Block 12 for mining and the economic challenges, an alternative mining method is proposed for the Target Mine Block 12 utilizing a Top-Down Sublevel open stoping. This mining method will produce $\pm$2 Million tons of broken ore at an average grade of $\pm$3.58 grams per ton. There will also be an additional cost-saving of $\pm$1,3 Billion rand due to narrow reef de-stressing no longer required, reduction in required development meters, labour, and no backfill to be placed into the Top-Down Sublevel open stope.

INTRODUCTION

Target Mine is situated adjacent to the town of Allanridge some 20 km from Welkom, as shown in Figure 1, and is the most northerly mine in the Welkom Goldfields area. The mine consists of a single surface shaft system with a sub-shaft (Target 1C shaft) and a decline. Ownership was attained by Harmony Gold Mining Company Limited in May 2004 (Harmony Annual Report, 2010).

Target Mine is mining at a depth of between 2200m to 2600m below the surface and is classified as a deep mine. The current mining method utilizes scattered open stoping, allowing only payable blocks of ground to be mined. For this reason, de-stressing must be done reducing the major principal stress to between 50 MPa and 60 MPa, eliminating high-stress blocks and allowing ring holes to be drilled perpendicular to the major principal stress. A bottom-up mining approach is used and the open stopes backfilled before mining the adjacent open stope, if economically viable. Block 12 is situated to the north of Target Mine as shown in Figures 2.

With improved geological and geotechnical information available as compared to 2017 and due to mining challenges, ventilation constraints the trackless development to "open-up" the Block 12 for mining, is behind schedule and the current economic challenges an alternative mining method is proposed for the Block 12 utilizing a Top-Down Sublevel open stoping. This mining method will produce $\pm$2 Million tons of broken ore at an average grade of $\pm$3.58 grams per ton. There will also be an additional cost-saving of $\pm$1,3 Billion rand due to narrow reef de-stressing no longer required, reduction in required development meters, labour, and no backfill to be placed into this open stope.

For the design of the open stopes, support requirements and de-stressing required for Block 12, the quality of geological and geotechnical information is critical.

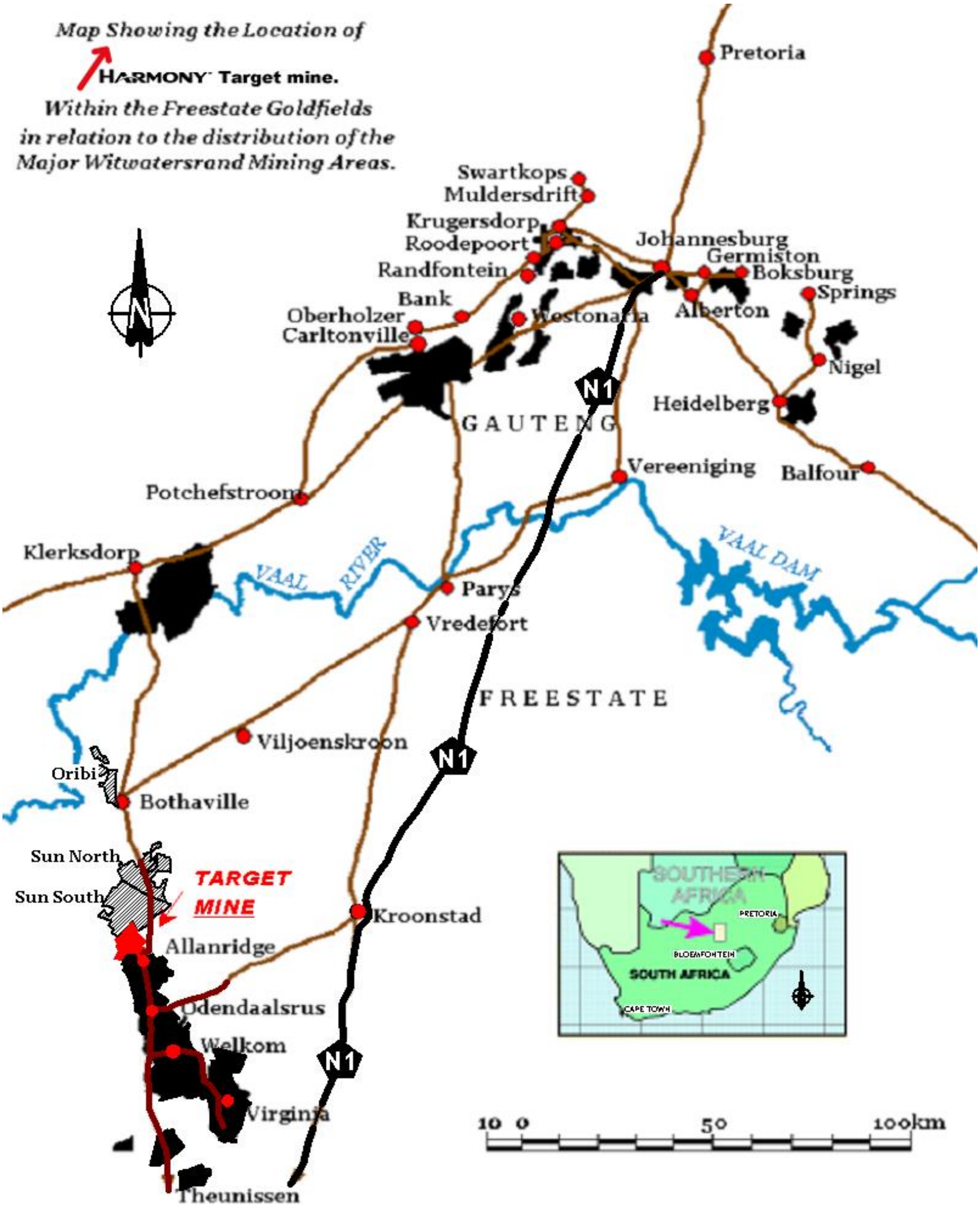

Figure 1 – Location of Target Mine (Harrison, 2010)

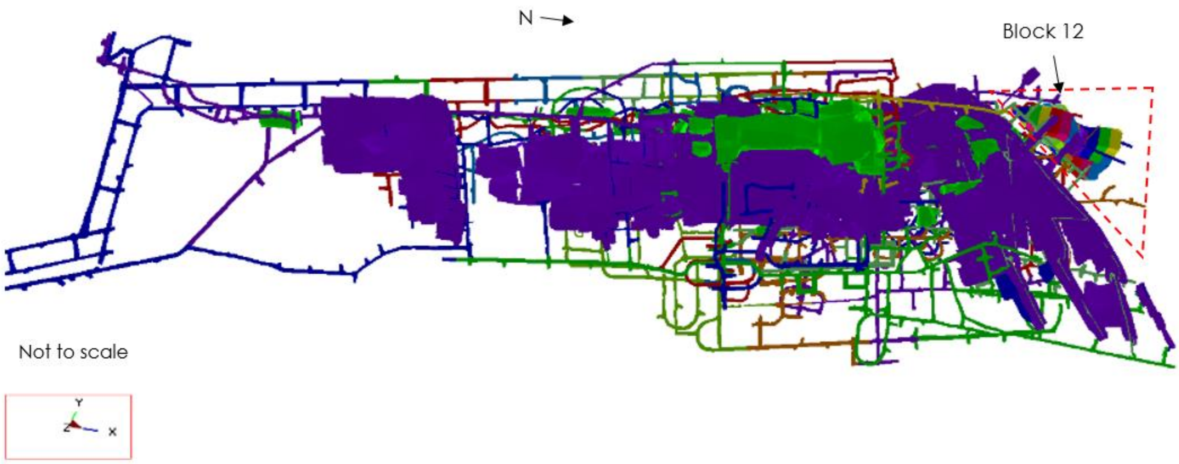

Figure 2 – Plan view of Target Mine and Block 12 respectively (Le Roux, 2020)

GEOTECHNICAL EVALUATION OF MINING BLOCK 12

To make informed decisions on the open stopes design, support requirements and expected ground conditions the following information is critical:

- Geological structures (faults, joints and dykes)
- The Uniaxial Compressive Strength (UCS) in MPa for all the relevant formations in which the reef drives, access development and return airways will be situated
- Possible Quartzwacke intersections
- Expected seismic response and risk.
- Excavation dimensions (Access development and size of orebody).
- Expected field stresses
- Rockburst and Gravity falls of ground historic data

GEOLOGY

The Block 12 is separated from the rest of the mining blocks on Target Mine by the Blast Dyke striking north-west south-east with small faults within the Block 12 striking east-west as shown in Figure 3. The economical reefs that would be mined in Block 12 will be the EA1 and EA3 of the Van den Heeversrust Member. The EA Zone comprises interbedded green to black, coarse to medium-grained argillaceous Quartzwackes (referred to on the mine as subgreywackes), interbedded with polymictic to oligomictic conglomerates and local quartzites. The EA assemblage as developed at Target Mine 1 Shaft (North), is markedly different from that at Target 3 Shaft (South) concerning the volumetric quantities of mature to immature sediments. Except for the EA1 with its EB footwall, and the EA8 and EA15 bands, there are no distinctive markers, which can be used for identifying the different reefs. The Eldorado Reefs sub-outcrop against the Dreyerskuil Reefs (Harrison, 2010).

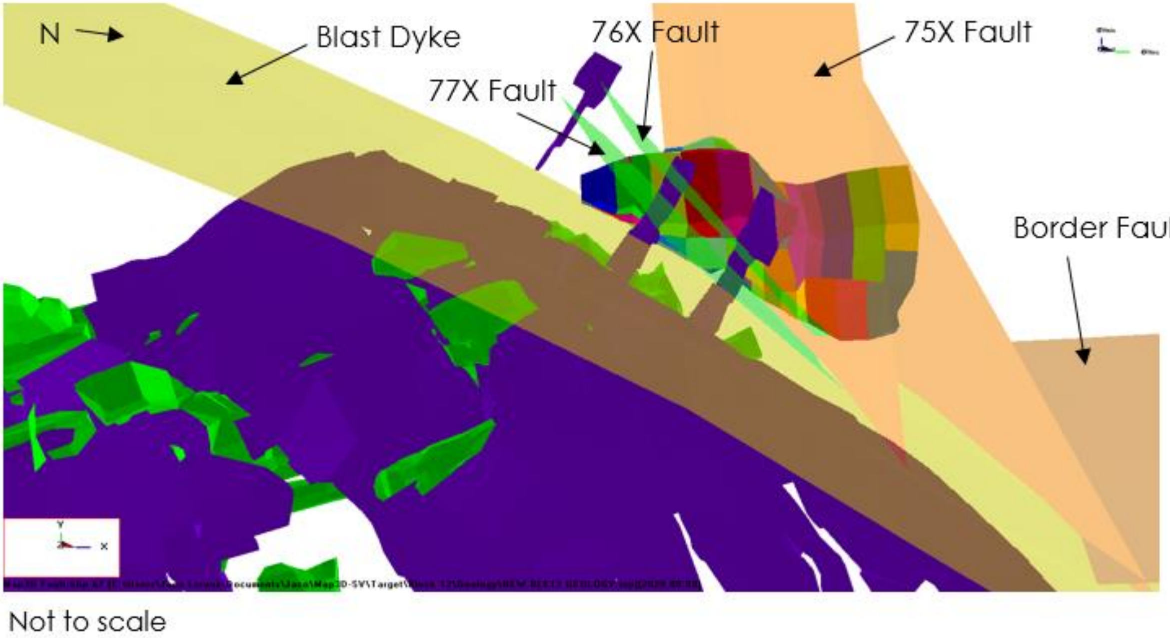

Figure 3 – Plan view of Block 12 geological structures (Le Roux, 2020)

The access development to the west of the orebody as shown in Figure 4 will be situated in the EB Rosedale Member, which is good to fair rock with a maximum and minimum RQD of 86% to 66%. The UCS for this formation ranged from 177 MPa to 223 MPa.

Indicated in Figure 4 the on-reef development and eastern access development will be situated in a wide range of formations ranging from the Quartzwackes 1QW to 7QW and the EA1 to EA7 of the Van den Heeversrust Member. The RQD for these formations ranges from very poor to very good rock. However, the UCS for most of the formations is greater than 200 MPa except for the 1QW with a minimum of 149 MPa and a maximum of 163 MPa. The weakest formation of the Quartzwackes is the 3aQW with a minimum of 128 MPa and a maximum of 153 MPa.

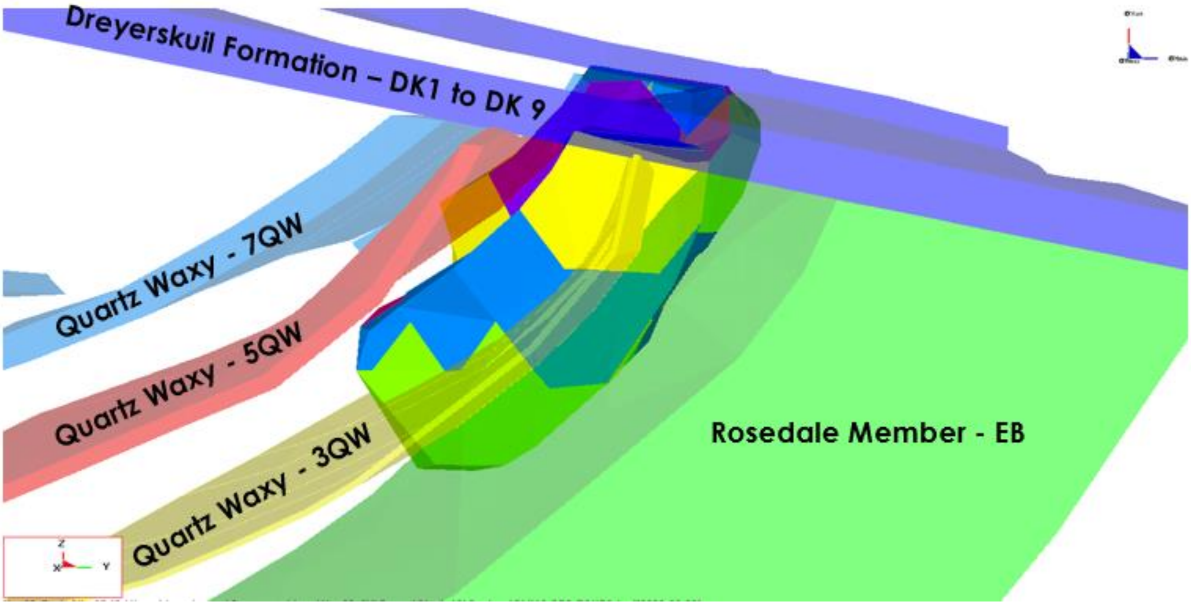

Figure 4 – Section view looking south indicating the geological formations to be intersected by mining excavations in Block 12 (Le Roux, 2020)

EXCAVATION DIMENSIONS

All service excavations such as access drives, ramps and return airways are planned to be blasted 5m wide and 5m high. All reef dives are planned to be blasted 4,5m wide and 5m high. The return airways at 287 level to 280 level will be raise bored at 90°.

MINING METHOD

Current Mining Method

A detailed internal report was done in which the support design and required de-stressing for the Block 12 development was discussed. The extent of the required de-stressing for Block 12 is shown in Figures 5. The initial design was done on the planned open stopes as given by the planning department with the expected development and available geological data at that time. In summary, a total of 142695 m^2 of de-stressing is required to mine the Block 12 when utilizing the scattered open stoping method.

However, before de-stressing can commence, access development will be developed into Virgin Stress conditions and at some areas through high-stress abutments. When de-stressed, significant stress changes can be expected at these excavations and the installation of secondary support consisting of weld mesh and is paramount to the stability of these access drives.

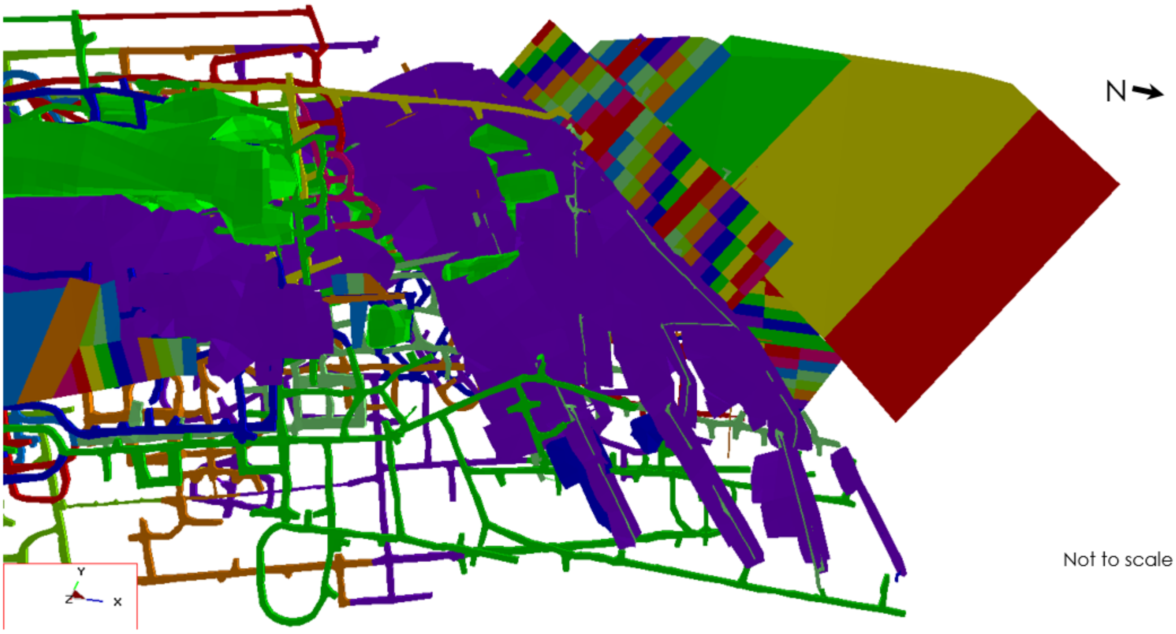

Figure 5 – Plan view of Target Mine and current planned Block 12 de-stressing (Le Roux, 2017)

Alternative Mining Method

With improved geological and geotechnical information available as compared to 2017, the alternative mining method considered for Block 12 is a Modified Top-down Sublevel Mining Method. In the Modified Top-down Sublevel Mining Method. The top massive will lead, creating a de-stressed window below for the bottom massives. A schematic representation of the Modified Top-down Sublevel Mining Method is illustrated in Figure 6.

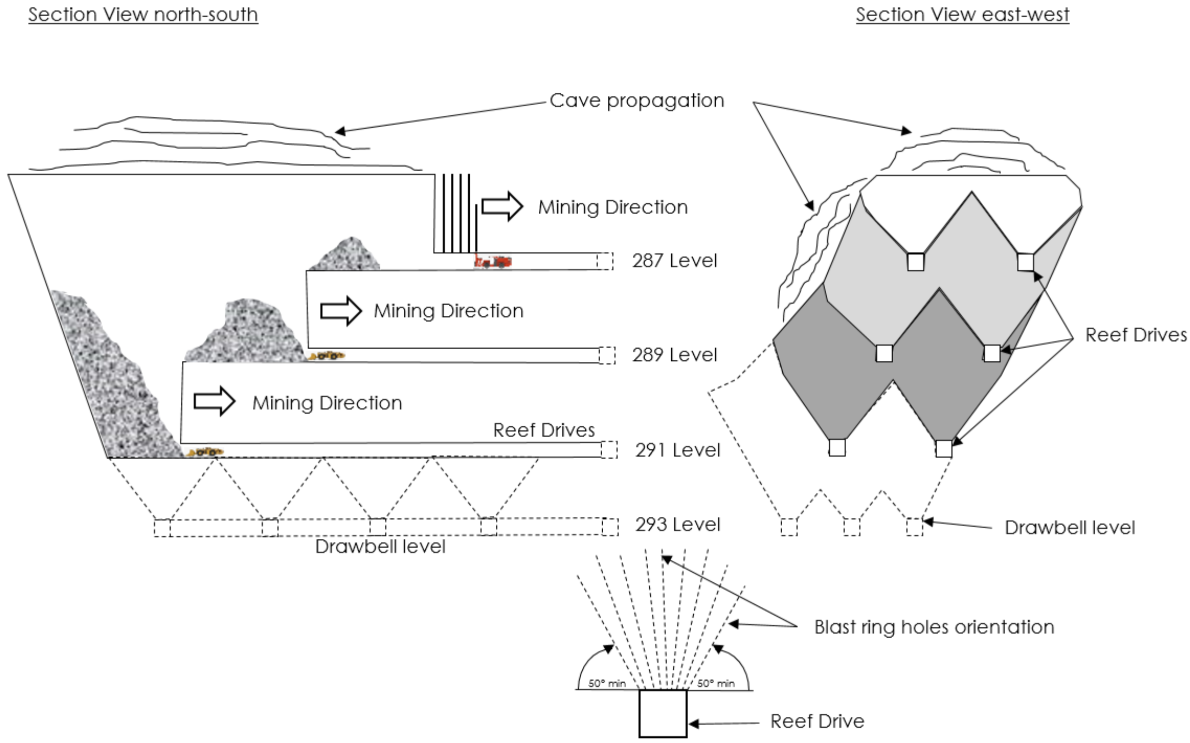

Figure 6 – Schematic representation of the Modified Top-down Sublevel Cave Mining Method at Target Mine (Le Roux, 2020)

NUMERICAL MODELLING

Excess Shear Stress (ESS)

Making use of numerical modelling the expected Excess Shear Stress (ESS) on the geological structures can be determined. According to Ryder (2002) the stress-drop distribution of the 'excess shear stress' (ESS $\tau_e = \tau - \tau_d$) is the constituent that drives the resulting ride on the ruptured plane, which could result in a seismic event on a geological structure. Accordingly, ESS τ_e is defined as follows:

$$\tau_e = |\tau| - \mu\sigma_n \qquad [1]$$

where τ is the absolute value of driving shear stress regardless of sign, $\mu = tan\varphi$ is the coefficient of dynamic friction, and σ_n is the normal stress acting on the fault plane. Aki & Richards, 1979 proposed a method for determining the magnitude of a shear-type seismic event by calculating the 'seismic moment', which is defined by

$$M_o = G \int Ride\ dA = GV_R \qquad [2]$$

whereby the seismic moment is simply given by the product of the strata shear modulus G and the volume of ride V_R over the rupture.

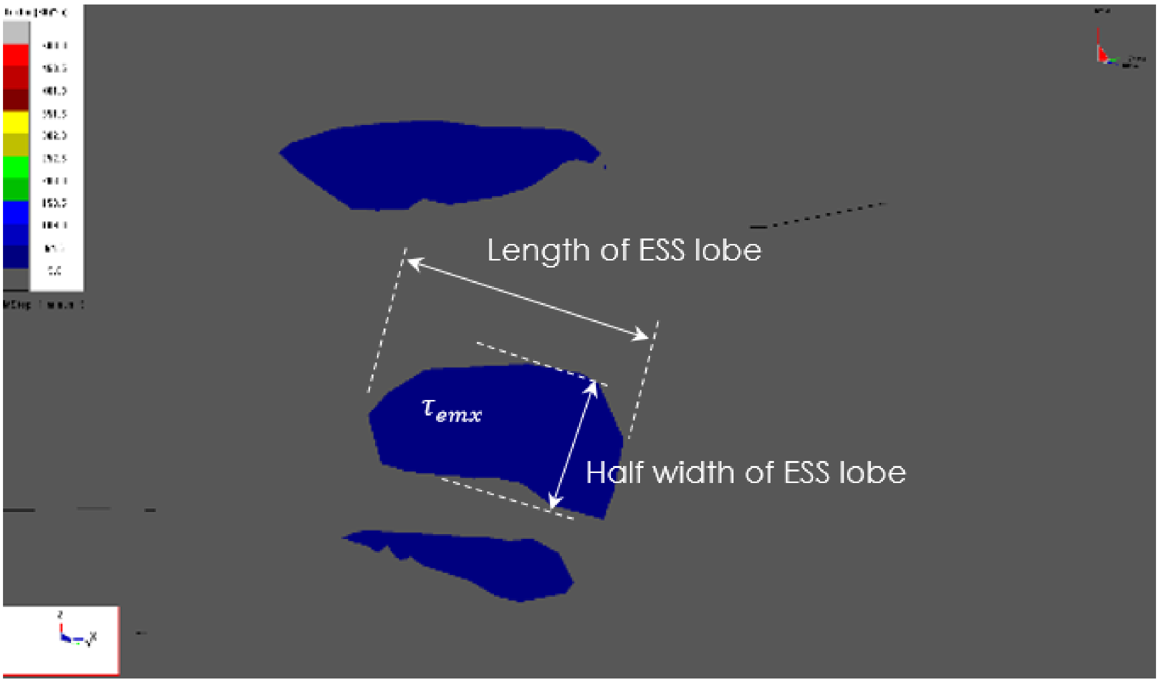

Figure 7 – Isometric view of an Excess Shear Stress (ESS) lobe on a fault plane (Le Roux, 2020)

By plotting the Excess Shear Stress (ESS) > 5 MPa on the geological structures, the ESS contours can be measured as shown in Figure 7. Sometimes, the modelled ESS contours on a plane will either roughly approximate a circle of radius a, or a rectangular area of length D and width $2a$ where a is the half-width in the direction of incipient slip as shown in Figure 6. In such situations M_o is defined as follows:

$$M_o \approx 1.7\, \tau_{emx}\, a^3 \qquad \text{[circular ESS contour]} \qquad [3]$$
$$M_o \approx 2.1\, \tau_{emx}\, Da^2 \qquad \text{[rectangular ESS contour]} \qquad [4]$$

where τ_{emx} is the maximum ESS on the rapture plane. Making use of the above mentioned equations either analytically or numerically, and together with the widely-used 'magnitude-moment' relationship (Hanks & Kanamori 1979)

$$1.5\, M = log_{10}\, M_o - 3.1 \; [M_o \text{ in MN-m}] \qquad [5]$$

an estimation of the Richter magnitude M likely to be associated with rupture on the geological structure can be calculated.

Three-Dimensional Stress in the Mining Environment

In long hole blast ring drilling, stress has a significant effect on the stability of these holes. It was found in previous open stopes being mined in high-stress conditions that the sidewall ring holes "dog-eared" and closed up as they scaled and subsequently had to be re-drilled. This is time-consuming and resulted in time delays when blasting the massive open stopes.

In Figure 8 the effect of stress on these holes is schematically represented. When the blast hole is drilled parallel to the major principal stress σ_1 only the minor principal stress σ_3 is acting on the sides of the hole. Depending on the UCS of the rock the hole should stay stable and no scaling encountered. It was found that these holes drilled between 50° and 90° to the horizontal in the hangingwall remain stable as shown in Figure 8 (b). However, for the blast holes drilled at an angle less than 50° in the sidewalls, it was found that these holes tend to scale due to the major principal stress σ_1 acting perpendicular to the axis of the hole as depicted in Figure 8 (a and b).

From the results, the stress at the Sublevel open stope will be high as expected and the stress vectors indicate that it would be parallel to the face in the z-direction. This is of great significance as this indicates that when drilling the blast ring holes in the hangingwall, these holes will be parallel to the major principal stress. The calculated stress levels will range from 80 MPa to as high as 100 MPa. The stress vectors indicate the orientation of the major principal stress and thus confirm that the hangingwall blast holes can only be drilled at a minimum angle of 50° plus from the horizontal.

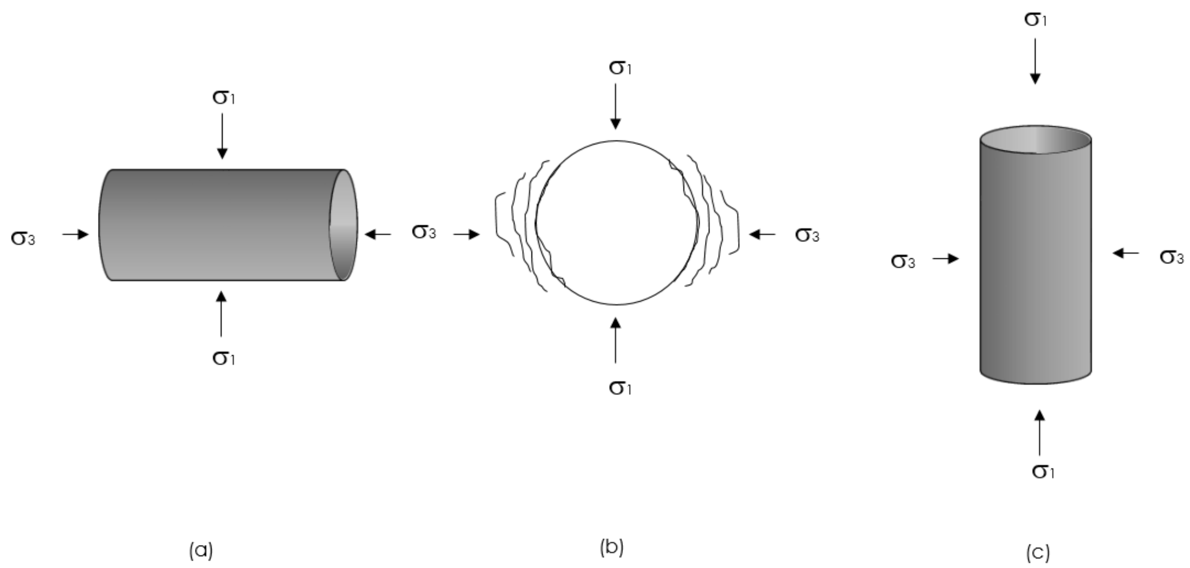

Figure 8 – Schematic representation showing the effect of major and minor principal stress on blast hole orientation (a and b) section view indicating expected failure for σ_1 perpendicular to excavation axis (c) no failure if σ_1 parallel to excavation axis (Le Roux, 2020)

DILUTION STRESS STRAIN INDEX (DSSI) AND DETERMINING DILUTION IN BLOCK 12 OPEN STOPE

Making use of obtained median mean stress value σ_m determined for the Block 12 open stope, the DSSI can be applied for major failure in open stope hangingwall and sidewalls in Map3D on the vertical grid planes. To calibrate the model, the Young's Modulus (E) and Poisson's Ratio (v) for previous open stopes in similar stress and strain conditions were used. The same Young's Modulus (E) and Poisson's Ratio (v) must be applied for all numerical modelling being done in Block 12. To apply the DSSI for major failure in the hangingwall and sidewalls of the Block 12 open stope in Map3D, the failure depth on the vertical grid planes are measured. The DSSI failure lobes can also be exported as a DXF file and compared to the design stope shape, to determine the expected dilution. Using this information the stope shape can be amended (reduced in size) so that the final shape corresponds with the actual required planned shape due to the expected failure depth. The flow chart shown in Figure 9 gives the detailed recommended approach (Le Roux and Stacey, 2017).

Applying the methodology shown in Figure 9, the open stope can be evaluated. Following the steps recommended, when plotting the results for mean stress in MPa versus volumetric strain in millistrains, there is a clear linear relation. Making use of Equation [6], hangingwall and sidewall failure in Block 12 open stope can be predicted by the following equation proposed for Target Mine, with ε_{vol} in millistrains (Le Roux and Stacey, 2017):

$$DSSI = \left(\frac{MEDIAN\ (\sigma_m)}{38.889\varepsilon_{vol}}\right) > 1 \qquad [6]$$

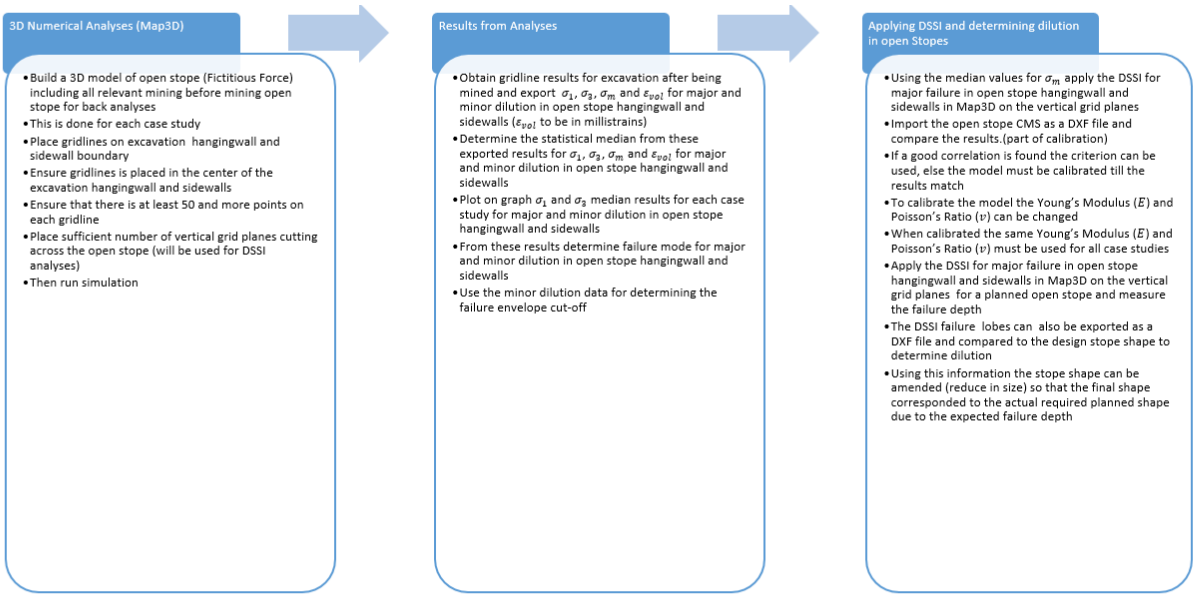

Figure 9 – Flow chart showing the detailed recommended approach for the application of the DSSI design criterion and determining dilution in open stopes (Le Roux and Stacey, 2017)

Applying the Dilution Stress-Strain Index (DSSI) the hangingwall and sidewall dilution is estimated at 172000 m^3 as shown in Figure 10.

Although the three-dimensional stress-strain environment plays a significant role in the stability of the massive open stope in Block 12, the rock mass properties will also have a significant impact. Evaluating the Block 12 Modified Stability Number (N') versus the hydraulic radius (HR) the expected stand-up time and dilution can be determined for the hangingwall and sidewalls. From the analyses, the following were estimated as tabulated in Table 1. The results indicate as the open stope stand for extended periods, the open stope will start to cave due to the large hydraulic radius.

Table 1 – Summary of the analyses of Block 12 open stope and expected dilution (Le Roux, 2020)

Open stope Hangingwall hydraulic radius	21.7 m
Open stope sidewall hydraulic radius	43 m
Maximum Hangingwall span	43 m
Maximum sidewall span	114 m
Q	0.895
Q'	7.875
Average UCS	230 MPa
Average Induced Stress at the centre line of open stope hangingwall	12.7 MPa
Estimated open stope stand-up time	1 to 2 months
Open stope volume	851892 m^3
Dilution volume from DSSI	171674 m^3
Calculated dilution from the modified stability number (N')	22%
Calculated dilution from the hydraulic radius (HR)	98%
Calculated dilution from DSSI	20%

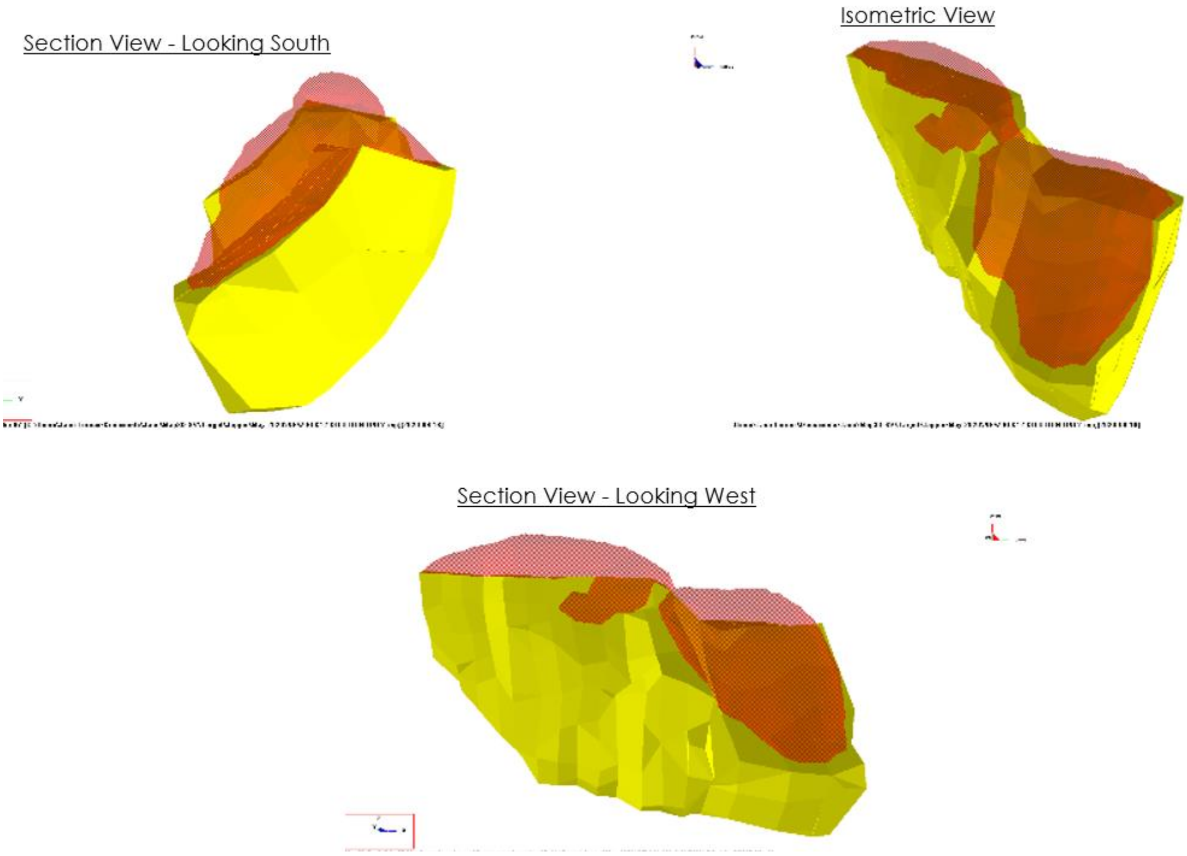

Figure 10 – Estimated hangingwall and sidewall caving expected in the Block 12 open stope indicated in red (Le Roux, 2020)

DESTRESSING OF SUBLEVEL OPEN STOPES

As the top Sublevel open stope is mining north, it creates a destress zone below. The destress created by the Sublevel open stope above as shown in Figures 11 and 12 is of sufficient size for the next level below and can mainly be contributed to the shape of the orebody. When the top sublevel stope above advanced 60m, the next level of Sublevel open stope can be mined. A minimum of 40m and maximum of 60m top lead must be maintained between each level. Thus the 287 sublevel stope must lead the 289 sublevel and the 289 sublevel must lead the 291 sublevel as shown in Figure 5. The open stope face must be mined inline on each level not creating high-stress abutments or lead/lags.

From the stress analyses, it is imperative to maintain a minimum of 25m skin to skin distance between all short term excavations (reef drive development) in Block 12. The sub-levels development must be maintained at 30m skin to skin vertical distance as to prevent stress interaction between these excavations and to avoid the abutment stress from the top sublevel open stope above effecting the reef drives stability.

However, the long term excavations (access, ramp and return airways) will not undergo the same stress changes and will be stable for the duration of mining Block 12. All long-term excavations must be developed >35m from the sublevel open stope orebody.

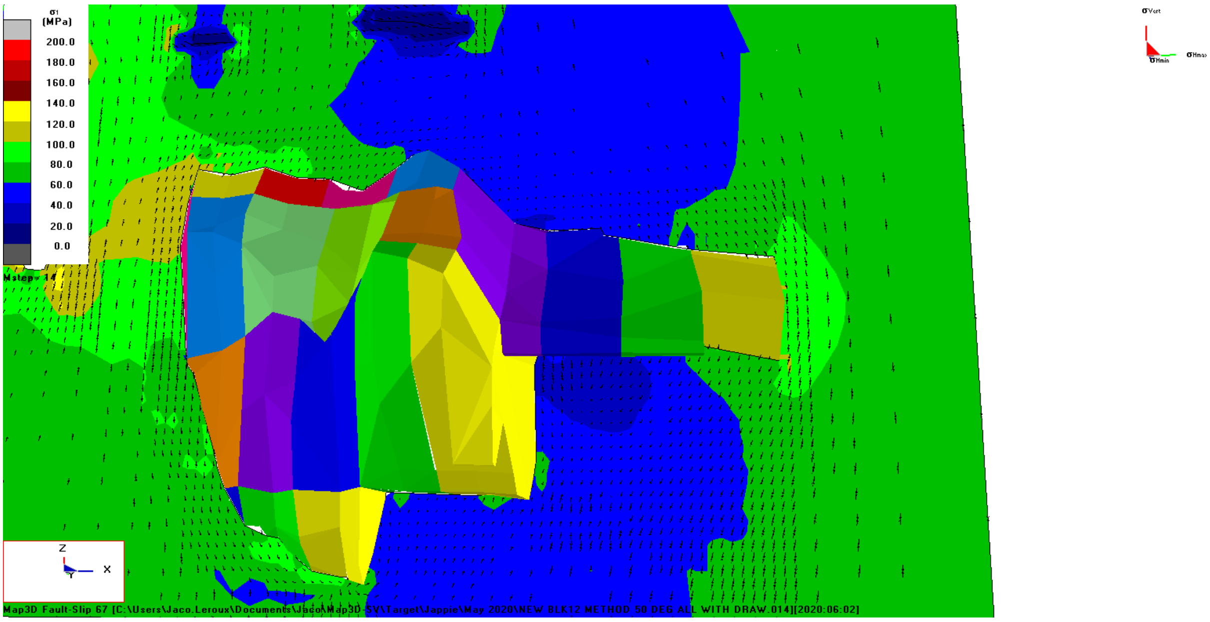

Figure 11 – Section view north-south showing destress in blue as mining progress (Le Roux, 2020)

Figure 12 – Section view east-west showing destress in blue as mining progress (Le Roux, 2020)

SUPPORT DESIGN FOR BLOCK 12

Numerous rock-related incidents and accidents were investigated during the period 2007 to 2020 in mechanized development. The results indicate that 47% of all rock-related incidents are seismic, of which 92% were from the sidewalls and 8% from the hangingwall. Rockbursts can be classified into five classes namely strainburst, buckling, face crush or pillar burst, shear rupture or fault-slip burst (Ortlepp and Stacey 1994; Ortlepp 1997).

From the rockburst back analyses, it was found that all were dynamically-induced rockbursts with damage caused by either energy transfer or significant dynamic stress increase from a remote seismic source. All of the rockbursts observed (indicated in yellow spheres) at Target Mine were located close to or in the high-stress abutment (indicated in red) around the de-stressing slot (indicated in purple) as shown in Figure 13.

Significant damage was observed at all the case study sites as shown in Figure 14. The bolt support on Target Mine consisted of 1,8m and 2,4m split sets spaced on a 1m by 1m pattern covered with 5.6mm, 100mm aperture mild steel weld mesh. During the rockburst investigations, split sets with striation marks were observed after being violently ejected during dynamic loading as shown in Figure 15.

It was also noted that in instances the split set base plates were knocked off as shown in Figure 16. Back analyses indicate that ejection is mainly in the direction normal to the sidewall, visible on the split sets as shown in Figure 16 and some slip along the bedding plane fault (Case study 1 (van Aswegen 2009)). It should be noted that, in all cases where no weld mesh was installed, the sidewalls were ejected. Areas covered with shotcrete only were also ejected.

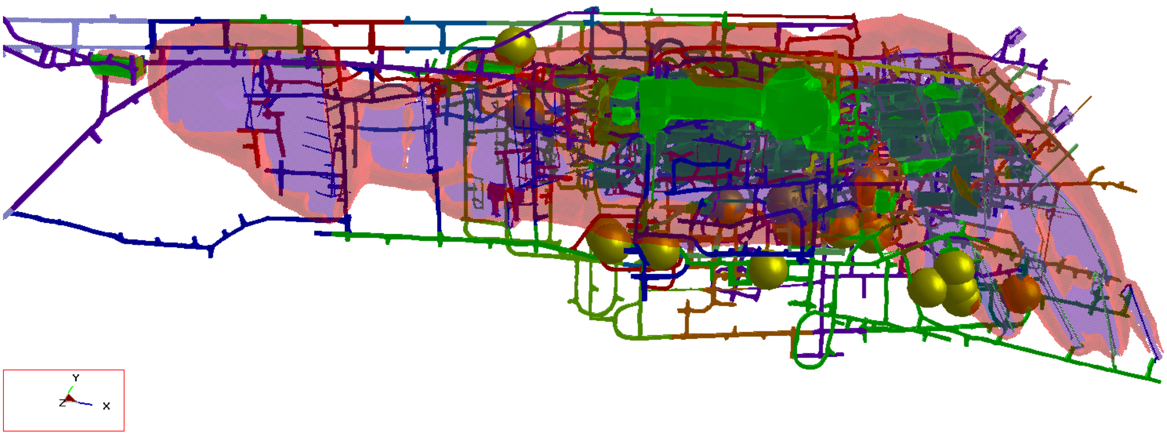

Figure 13 – Plot of 29 rockbursts recorded on Target Mine (Le Roux, 2020)

Figure 14 – Photo showing the extent of rockburst damage (Le Roux, 2020)

Figure 15 – Photo showing striation marks on split set from dynamic loading after being violently ejected (Le Roux, 2020)

Figure 16 – Split set indicates ejection mainly in the direction normal to the sidewall and some slip along the bedding plane fault (van Aswegen, 2009)

Part of an effective rockburst support strategy requires an understanding of the rockburst source mechanism and stress environment. When conducting back analyses on rockbursts the following information is required; original excavation dimensions before the rockburst; excavation dimensions after the rockburst; major principal stress at rockburst position; the mass of ejected rocks; Shear Modulus; support installed and condition of support; coordinates of rockburst; rockburst from hangingwall, sidewall or both; Local Magnitude of a seismic event and its coordinates.

The outcome of the back analyses is dependent on the quality of the available information and is essential to the support design process. Ground support design strategy requirements for static and dynamic loading conditions in mechanized development are presented in Le Roux, 2020.

CONCLUSIONS

During the numerical evaluation of the geological structures making use of the Excess Shear Stress criterion, it is evident that when mining nearby the Blast dyke or 75X fault could result in slip failure resulting into large magnitude seismic events.

As the top Sublevel open stope is mining north, it creates a destress zone below. The destress created by the Sublevel open stope above is of sufficient size for the next level below and can mainly be contributed to the shape of the orebody. When the top sublevel stope above advanced 60m, the next level of Sublevel open stope can be mined. A minimum of 40m and maximum of 60m top lead must be maintained between each level. Thus the 287 sublevel stope must lead the 289 sublevel and the 289 sublevel must lead the 291 sublevel as shown in Figure 6. The open stope face must be mined inline on each level not creating high-stress abutments or lead/lags.

From the stress analyses, it is imperative to maintain a minimum of 25m skin to skin distance between all short term excavations (reef drive development) in Block 12. The sub-levels development must be maintained at 30m skin to skin vertical distance as to prevent stress interaction between these excavations and to avoid the abutment stress from the top sublevel open stope above effecting the reef drives stability.

As mining progresses, major stress changes will be encountered in the short term excavations. The Drawbell development will experience stress interaction between the 294 level excavations if developed to early in the mining stage. However, the long term excavations (access, ramp and return airways) will not undergo the same stress changes and will be stable for the duration of mining Block 12. All long-term excavations must be developed >35m from the sublevel open stope orebody. Ring holes to be drilled 50° plus to the horizontal, parallel to the major principal stress.

Primary and secondary support to consist of weld mesh pinned with resin bolts on and 100mm of wetcrete at the Quartzwacke 3aQW intersections in the reef drives and long term excavations. The distance from the face for the weld mesh will be determined using the Q-system as development progresses. The length of bolts to comply with the required static and dynamic support resistance requirements for Target Mine.

The hangingwall and sidewall failure for the Top-down Sublevel Mining Method was estimated by making use of the Dilution Stress-Strain Index (DSSI), Modified Stability Number (N') and hydraulic radius (HR). The Dilution Stress-Strain Index (DSSI) is estimated at 171674 m^3 with an estimated dilution percentage of 20%. Although the three-dimensional stress-strain environment plays a significant role in the stability of the massive open stope in Block 12 the rock mass properties will also have a significant impact.

The estimated dilution from the Modified Stability Number (N') is estimated at 22% with an open stope stand-up time of 1 to 2 month. As the hangingwall and sidewall beam start to fail due to the excessive hydraulic radius (HR) the cave will continue to propagate up to the Ventersdorp Lavas where it should stop propagating as observed with the MOS 1267 open stope in Block 1 on Target Mine.

Advantages

- No need for NRM de-stressing
- Make use of Sublevel open stope above to destress open stope below
- Mining on retreat, away from the seismically active Blast dyke
- Less Trackless development required
- Trackless equipment stay on one level
- Ventilation will be returned through the massives to RAW thus reducing:
  - The heat from trackless equipment
  - Dust during loading
  - Diesel particulate matter (DPM)
- No backfill will be required for Block 12 making use of Sublevel Cave Mining
- Reduced hauling distance to 291 level tips to the new Crusher

Disadvantages

- Have to mine all of the massive orebody, which includes high and low-grade ore
- All access and reef drives to be within the competent ground and to avoid Quartzwacke 3aQW where possible.
- Dilution from the hangingwall and sidewall can be expected
- To control the dilution, waste tags on each level can be placed to track waste or low-grade ore

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