The role of stress and geology on the design of block cave mining sequences and layouts - a case study

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Abstract

While high production rates are important for the profitability of a mine, the influence of geotechnical engineering cannot be ignored. In block caving, a high-stress level is required for cave propagation; this is one of the core elements for ore recovery. Therefore, stress distribution and geological structures play a major role in the planning and layout design of the mine. This paper explores the influence of stress and geological features on the design of the mine from the feasibility study phase. The geology and stress measurement of the mine were determined through logging and overcoring, respectively. This study found that while production rate is the primary operational consideration, the long-term layout design of the undercut face advance, face angle, drawpoint spacing, and undercutting sequence is mainly governed by the stress orientation and major geological structures. Moreover, widely spaced drawpoints result in isolated draw zones, consequently, resulting in ore loss and early dilution whereas closely spaced drawpoints affect the stability of the major apex pillar. This paper also provides insight into how operations can leverage stress distribution to optimise mine layout and safety in massive mining methods.

Keywords

block caving, advanced undercut, drawpoint spacing, leads and lags, isolated draw zones

Introduction

Block caving is a large-scale underground mining method primarily used for extracting low-grade, massive ore bodies, as shown in Figure 1. The bottom of the orebody is undercut by blasting to initiate the caving of the rock mass through gravity (Diaz et al., 2024; Melati et al., 2023). The undercutting process generates mine-induced stress distribution, contributing to the progressive caving of the rock mass. Moreover, deep mining is characterised by rock fractures and unstable hangingwalls that challenge the safety of mine workers and equipment (Wagner, 2019). Considering this, strategic management of mining-induced stress, seismicity, and air blast should be the core of mine design and planning in block caving operations (Cuello, Newcombe, 2018). This paper aims to evaluate the role of stress distribution and geological structures on block cave mining sequence and the mine layout. That is, the face shape, drawpoint spacing, and the vertical distance between the production and undercut level. A thorough knowledge of the geological structures of the mine in all three dimensions, in conjunction with the geotechnical properties of the rock mass, dramatically impacts the long-term design of the mine (Murphy et al., 2016). This is because the undercut and production tunnels intersect the weaker zones, whereas the mine design and sequence must remain open for the life of the production level (Tukker et al., 2016).

Several studies have examined the influence of geotechnical parameters on block-cave mining operations. Morales et al. (2024) reviewed several studies on the challenges of orebody cavability prediction in block caving. These authors were able to argue that rock mass characterisation is the foundation for reliable estimations of the rock mass quality for design applications. On the other hand, Hadjigeorgiou (2012) stressed that there is a lack of quality data in underground mines due to mapping difficulties caused by limited access, walls covered with shotcrete, and poor visibility On the other hand, poor visibility significantly impacts the reliable estimation of rock mass strength. Massive mining methods such as block caving often result in conditions of high-strain energy stored in the rock. Mining activities can result in the release of stored strain energy, consequently leading to dynamic rock failure (Bewick, 2021; Roy et al., 2023).

Bartlett and Nesbitt (2000) studied how stress-induced damage in tunnels in a cave mining environment can influence mine planning. The study reveals that high-stress levels are set up in the

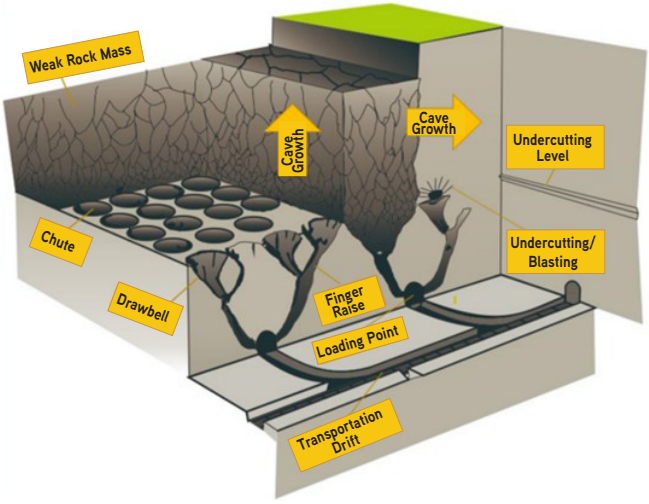


Figure 1—Block caving layout (Melati et al., 2022)

abutment zone around the perimeter of the caving area, which can affect tunnel stability at 20 m from the cave front. The authors add that the most stable face shape is concave or V-shaped towards the cave. This face shape has the advantage of allowing low abutment stresses to develop at the apex on both the undercut and extraction levels. High abutment stresses develop towards the edge of the cave. A straight-face shape is often more challenging to control than the V-shape and does not provide the low-stress area that the V-shape does (Bartlett, Nesbitt, 2000). The V-shaped cave front has a shorter face length compared to a straight-face geometry. In contrast, longer straight faces tend to advance more slowly, leading to higher stress concentrations along the face due to limited relief of abutment stresses. In support of the previous statement, Van As and Guest (2020) also add that cave design aims to engineer control over the cave's behaviour and performance. Therefore, a good understanding of the geotechnical domains, their spatial distribution, their rock mass characteristics, and their response to the stress regimes induced during the various stages of caving is required. Although there are several great studies on the effect of stress on the mining layout in block caving, there is a lack of studies holistically integrating geotechnical analysis with mine design in block cave operations. Therefore, the main objective of this study is to investigate the role of stress and geological structures on the design of mining sequences and layouts in block cave mining.

Geological setting

This study was conducted at Palabora Mining Company (PMC) in South Africa, Limpopo Province, Phalaborwa. The Palabora Copper Igneous Complex is a foskorite-carbonatite pipe complex with an area of 20 km2 that resulted from an alkaline intrusive cycle into a host Archaean granite. The copper ore body is an elliptically shaped vertical pipe with an area of 1 km2. The pipe intruded at a late stage into the central core of the PMC Igneous Complex. The pipe, as illustrated by Figure 2, consists of foskorite, banded carbonatite, and transgressive carbonatite. The composition features iron and copper mineralisation, especially magnetite, bornite, and chalcopyrite. Considerably later in the formation of the complex, the area was crossed by numerous dolerite dykes (Dixon, 1979). The central core is crossed by dolerite dykes trending NE-SW. The same basic arrangement persists for the full depth of the known deposit, although there is much local variation in all units. The dykes dip steeply to the west, as such move with increasing depth. The dolerite dykes intruded at a much later time than the other units and it appears that this occurred at a much shallower depth, when the wall rocks behaved in a brittle manner, giving the dykes their relatively regular thickness and form. Due to the declining ore grade in the first cave (Lift I), PMC is developing the Lift II project, which is a continuation of the block cave below the existing Lift I cave.

During the initial development of Lift II, the mining direction was configured perpendicular to the prevailing dyke orientations. This configuration was informed by early numerical modelling of Lift II, where stress assumptions were based on a back-analysis of the in situ stress field undertaken by Itasca Consulting in 2009. This back-analysis suggested that the stress regime was not hydrostatic but that the major principal stress is likely sub-horizontal, with

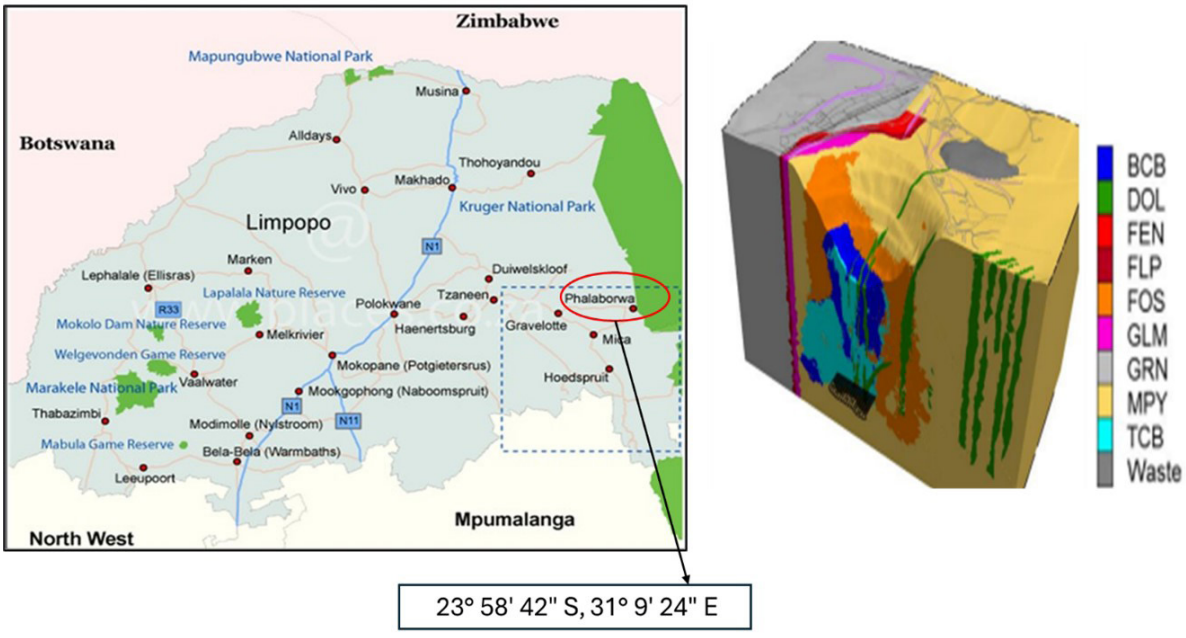


Figure 2—A map showing the location of PMC and the sectional view of the PMC's orebody

major principal horizontal stress (σH) = 2σz and minor principal horizontal stress (σh) =1.5σz (Van As, 2014). However, this orientation of the mining face, perpendicular to major geological structures (i.e., dykes and parallel to a fault), subsequently presented significant stability challenges. Dykes, due to their distinct mechanical properties, are known to absorb and release strain energy, which can result in rock bursts when disturbed. Consistent with this, stress-induced damage was observed throughout the Lift I infrastructure and during the early development of the Lift II infrastructure. Consequently, these observations necessitated further investigations to explore alternative face directions. Following these findings, a revised lower in situ stress regime, with a horizontal to vertical stress ratio (K) of 1.2:1, was subsequently adopted for the Lift II analysis (Sainsbury, 2016). The application and implications of this revised stress regime will be elaborated further in the Methodology section.

Methodology

This section discusses the steps followed in collecting raw data used during the mine planning process. The data from exploration drilling, cover drilling, and field observations were used to investigate the effect of stress and geological structures on the orientation of large excavations, mining sequences, and mine layout.

Geotechnical domains

The rock mass properties of the underground mine were initially determined through the mapping of the previous open pit before underground mining could start. The pre-feasibility study for Lift II was informed by extensive geotechnical data, derived from logging over 150 drill holes, totaling more than 57,500 m. Complementary geotechnical characterisation was provided by a geophysical survey that incorporated an acoustic televiewer (ATV) and other down-hole logging tools. This work was aimed at subdividing the total rock mass into geotechnically similar zones of similar characteristics in what is known as geotechnical domaining (Laubscher, 1994). This was done with the understanding that all the rocks within a domain exhibit similar engineering characteristics. However, the parameter/s used to subdivide an orebody (or any rock mass) into domains vary. In any type of rock, these variables might be the lithological composition (including alteration), the type or intensity of fracturing, the orientation of fractures, the strength of the rock material, or any combination of these parameters.

For the Lift I cave, the orebody within the zone of influence of the cave was divided into 3 structural domains, namely, the East, the Ramp Dyke, and the West Zones. These domains were further subdivided into "well jointed" and "less jointed" zones based on the joint spacings derived from the open pit mapping and drill core logging (where a joint spacing of 2 m separates the zones). The sub-domaining into "well jointed" and "less jointed" zones was to improve the accuracy of the fragmentation predictions. Various analyses established a 30:70 ratio between the "less jointed" and "well jointed" zones. The geotechnical domains for Lift II are based on lithology, namely, the branded carbonatite (BCB), dolerite (DOL), foskorite (FOS), micaceous pyroxenite (MPY), and transgressive carbonatite (TCB). The properties of the geotechnical domains are summarised in Table 1.

Table 1

Hoek-brown failure properties of the geotechnical domains (Van As, 2014)

Geotechnical domain	σ_{ci} (MPa)	mi	GSI	m_b
BCB	22.9	22.9	22.9	22.9
DOL	24.1	24.1	24.1	24.1
FOS	25.2	25.2	25.2	25.2
MPY	17.4	17.4	17.4	17.4
TCB	28.0	28.0	28.0	28.0

Stress distribution/orientation

The stress orientation of the rock mass for Lift II was determined through overcoring in foskorite on the Lift II production level. It stands out in rock mechanics since it is the only method capable of obtaining the magnitude and direction of the full three-dimensional stress from a single OC test (Li et al., 2024). Specifically, a revised in situ stress regime was proposed based on the stress measurements that were conducted. A summary of both the initial (as discussed in the background section) and the revised Lift II stress conditions, which informed the present analysis, is presented in Figure 3.

The modelling input values are summarised in Table 2.

The revised stress regime differs from the initial Lift II regime in the following aspects:

- The σ_1 and σ_3 orientations have been swapped. In other words, σ1 was previously striking NW-SE, but it is now vertical. Conversely, σ_3 was previously vertical, but it is now striking NW-SE.

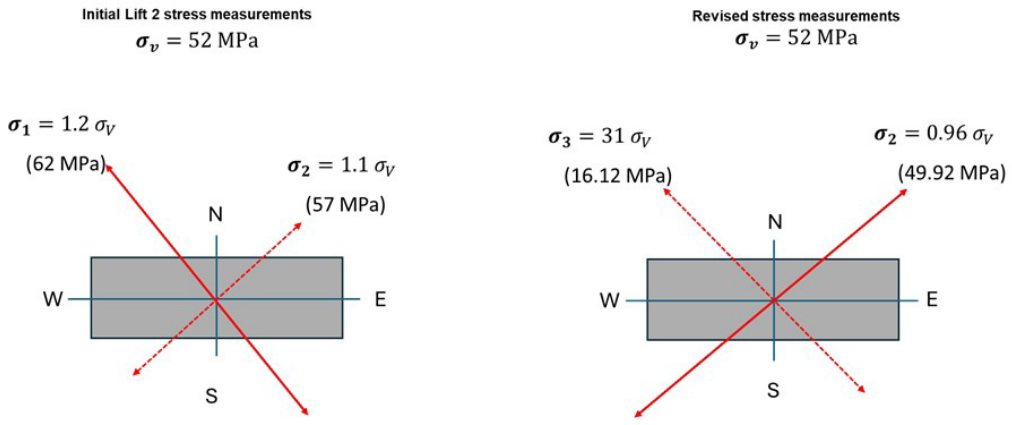


Figure 3—Initial Lift II and revised Lift II in situ stress conditions (Sainsbury, 2023)

Table 2
Simulated in situ stress regime (Sainsbury, 2023)

Stress	Magnitude (MPa)	Dip (o)	Dip direction (0)
σ_1	ρgH	90	0
σ_2	0.96*σ_1	0	058
σ_3	0.31*σ_1	0	148

- The horizontal stress magnitudes are lower. Indeed, striking NW-SE, the stress magnitude has now decreased from 62 MPa to 16 MPa at the Lift II production level. However, the deviatoric stress (difference between σ1 and other stresses) is higher at 0.96 and 0.31, as opposed to 1.2 and 1.1). Stress measurements indicated that both horizontal principal stresses are lower than the vertical stress, identifying the vertical stress as the major principal stress.

The initial response of the Lift II production level and cave initiation supports the revised stress regime (Sainsbury, 2023).

Results and discussion

Mining method

This section discusses the influence of the measured stress on the mining layout of Lift II. The layout specifically refers to the undercutting method, the face advance rate, the face angle, and the face length.

Advanced undercut

To minimise stress damage and increase rehabilitation requirements in extraction levels, PMC opted for advanced undercutting techniques. In simple terms, the advanced undercut method (see Figure 4) was selected to ensure the stability of the extraction level for the mine's life. The advantage of advanced undercut over post-undercut is that large unsupported drawbell excavations are not subjected to high abutment stresses, and less support rehabilitation is required in areas where undercutting precedes production-level development. On the other hand, post-undercutting results in stress-induced damage to the draw horizon level, therefore, it would be prudent that the undercut should be advanced first, and the draw horizon should be developed in de-stressed conditions. This approach aligns with established principles in block caving, as Butcher (1999) and Laubscher (2000) concur that stress increase associated with undercutting is a significant factor that influences the stability of the production level. Indeed, a fundamental principle for mitigating draw horizon damage, articulated by Butcher (1999), is the implementation of advanced undercutting within the block cave. Figure 4 differentiates the two methods.

Undercut face advance rate

The rate at which the undercut face is advanced is critical as the rock mass ahead of the undercut face is subject to high abutment stresses. The slower the undercut advances, the greater the deterioration of the rock mass, and the more difficult it is to successfully blast the face. To put it another way, slower advances result in creep damage due to stress build-up, which then increases the probability of seismicity (Sun et al., 2022). Conversely, rapid undercut face advance, where the face is greater than 50 m–60 m ahead of the last line of drawbells, leads to the formation of a stress shadow. This acts as an abutment stress concentrator, which typically results in large drive deformations and rockbursts.

Before development, the average advance rate of the Lift II undercut was initially planned at around 3,400 m²/month, equating to approximately 11 m/month. The current advance rate is 10 m–15 m/month, which still complies with standard practice (Crook, Prince, 2018). It is important to adhere to the standard advance rate since a slower advance rate increases the stress-induced damage. This phenomenon is supported by Butcher (1999), who adds that stress-induced damage increases with a reduction in the rate of advance of the cave line. The undercut abutment stresses reach the maximum magnitude when the undercut area equates to the required hydraulic radius of the block.

Undercut face angle

The initial undercut face was designed based on the initial stress orientation of the Lift II model to be initiated from the SE to NW, with an undercutting face striking NE-SW. However, based on the groundwork stress measurement done in 2017, the initial undercut long face orientation would have been parallel to the major

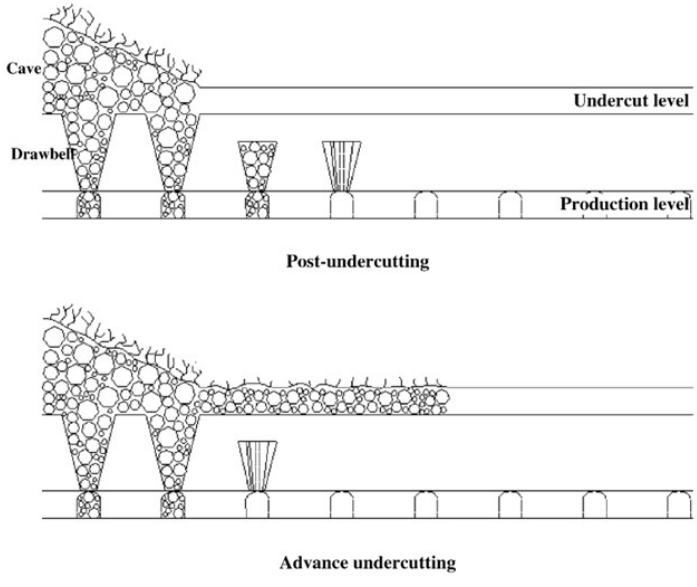


Figure 4—Development sequence of post and advance undercut (after Trueman et al., 2002)

principal stress and the major dolerite dykes (Groundworks, 2017). This would have had the potential to cause large slip failures posing a risk of unsuccessful execution of the undercutting. Dolerite dykes display brittle behaviour, making them susceptible to sudden failure under high-stress conditions (Ledwaba, 2012).To mitigate against the potential for large seismic risk, an undercut face design change was implemented to ensure that the long-undercut face advance is perpendicular to the major principal stress and dolerite dykes. The current mining direction in Lift II is from NE to SW, where the major geological features (dykes) are approached perpendicularly. The current face shape and undercut advance are depicted in Figure 5.

The initial angle of the undercut face advance was governed by the major horizontal stress based on the initial stress measurement. This angle was predominantly orthogonal, which was the best practice for reducing abutment stresses in the undercut face. However, following the updated stress regime orientation, it became apparent that the eastern face of the initial undercut wedge, as initially planned, would advance parallel to both the major horizontal stress and major dykes. Consequently, the direction of the face was changed to avoid this unfavourable condition. Fortunately, the extent of the NE advancing undercut face was limited, which helped to minimise its exposure to these problematic dykes during this transition.

Undercut leads and lags

The differential distances between adjacent faces (drill drives) are known as the leading and lagging distances. The greater the leads or lags between adjacent faces, the greater the stress differential. The objective is generally to minimise the lead and lag distances so that the tangential stresses are maintained in the undercut face while aiding in its stability by adding confinement to the rock mass. In practice, the operating lead-lag distance is between 10 m to 15 m (maximum) and ideally no more than 2 to 3 rings. Note here that blasting rings are spaced 2 m apart around the Lift II cave. As such, the lead-lag distance of the mine is currently at 6 m–12 m (see Figure 6). It is worth highlighting that the rock mass conditions of each mine differ, therefore, the lead-lag pattern is not always one-size-fits-all. Thus, the lead-lag distance was chosen based on the depth and stress conditions of the surrounding rock. As mining depth increases, the corresponding stress conditions also increase. Therefore, lead–lag pattern helps to spread out the abutment stress zones, lowering their magnitude and reducing the potential for large stress build-ups.

Undercut face length

The length of the undercut face is a function of the undercut face angle. The longer the face, the more difficult it is to construct a sufficient number of drawbells behind the face to allow it to keep moving. Practical empirical evidence suggests that an undercut face length of over 450 m is impossible to advance at a reasonable rate (Ross, 2018), as the construction rate for drawbells behind the face cannot be achieved. Typically, an average construction rate of 5-6 drawbells/month is the norm for drawbells (Pascoe et al., 2008). The maximum undercut face length planned for Lift II was 250 m. This is considered manageable, and the mine is still maintaining a face length of not more than 240 m. Long-face shapes over 300 m are difficult to manage from the point of view of ground stability control. These shapes also affect the advancement rate that can be achieved in a particular time. Consequently, a slow advance rate results in excessive abutment build-up, which in turn leads to the deterioration of undercut drives. This is because when undercutting is not advancing as quickly as planned, some areas in the cave will not cave as expected. As a result, this causes some localised stress on the abutments that will become difficult to successfully undercut.

Extraction level

The extraction level is designed to maximise ore reserves. As such, it should remain stable for the life of the mine to ensure maximum ore reserve recovery. The stability of the extraction level is often affected by the ore extraction activities, resulting in tunnel convergence, concrete slabbing at the walls, and sometimes closure (Castro et al., 2020). In granular material, such as caved rock ore, vertical stresses are significantly lower than total column weight because of the arching effect generated by shear stresses due to the rock friction. When the granular material is underflowing (flowing beneath the broken mass), at least two main zones, the movement zone and the stagnant zone, can be identified. In the movement zone (or draw zone), porosity increases, and vertical stresses decrease due to flow, while in the stagnant zone (or non-draw zone), vertical stresses increase. Castro (2006), through his experimental studies, has demonstrated that stresses can be transferred from the movement

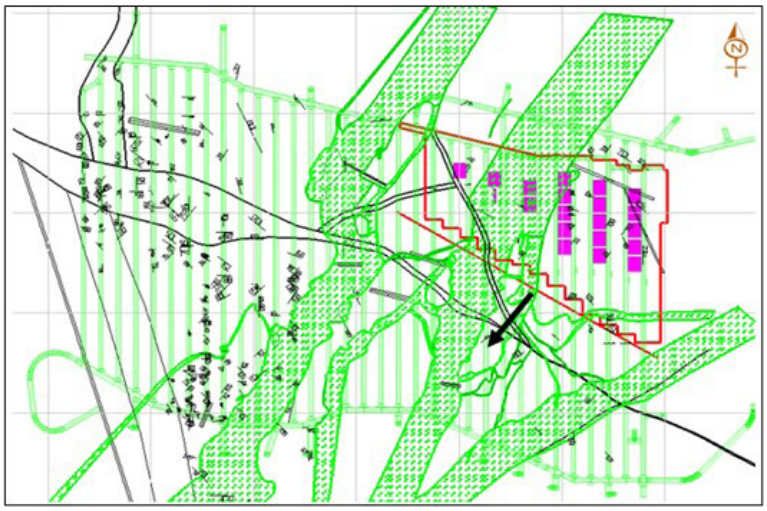
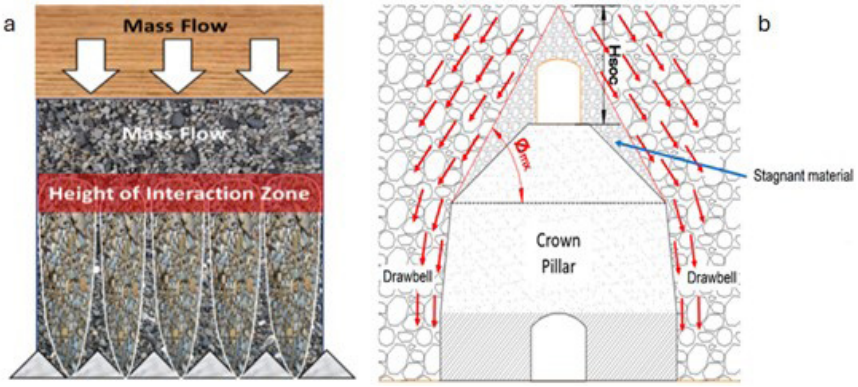


Figure 5—Revised Lift II undercut face advance direction; the green structures crossing through diagonally are the dolerite dykes (Sainsbury, 2016)

Figure 6—PMC Lift II undercut face and leads/lags (Sainsbury, 2016)



Figure—7(a) Illustration of interacting draw zones (after Laubscher, 1994); (b) Illustration of stagnant material (after Morales et al., 2024)

zone to the stagnant zone during flow. Then, induced vertical stresses over the production level depend on the movement of the gravity flow. Ngidi and Pretorius (2010) also emphasised that good draw control prevents stress concentration damage on the extraction horizon. Palabora Mine is currently using Gemcom's Personal Computer Block Cave (PCBC) systems for the draw strategy. Even draw is applied, ensuring maximum ore extraction from the reserves.

Drawpoint spacing

Drawpoint spacing is governed by the interaction of adjacent draw zones, amongst others. The interaction of adjacent draw zones refers to the point where the draw zones of two adjacent drawpoints meet (Figure 7a). It is worth noting that ore flow will occur when adjacent flow zones are spaced to allow interaction at a given height (Castro et al., 2020). The size of the ore fragmentation also dictates the draw-cone diameter. According to Laubscher (2000), the standard guideline is that finer fragmentation requires smaller drawpoint spacing whereas coarse fragmentation requires bigger draw zone spacing. Most importantly, drawpoint spacing must be related to the draw zone spacing, instead of being dictated by the size of the load haul dump (LHD) trucks. The isolated draw zone (IDZ) diameters for the averages of all rock types are approximately 12 m–13 m. This suggests an optimal drawpoint spacing of 32 m (drive centres) by 16 m (drawbell centres) to ensure an interactive draw. This design choice was primarily driven by two critical factors: the operational requirement to accommodate large load-haul-dump (LHD) equipment, and the geotechnical objective of improving the stability of the extraction level.

The drawpoints at Lift II are spaced 17 m apart centre to centre. From a business point of view, drawpoint spacing determines the ore reserve recovery of the mine. That is, as the spacing between drawpoints increases, there is a greater amount of non-recoverable ore (marked as "stagnant material" in Figure 6b). This is due to the increased separation along the major apex, generating an increase in the height of the interactive zone (HIZ) and leaving more ore between the drawpoints. It should be noted that the Lift I drawpoints are spaced too widely to facilitate an interactive draw, and this has ultimately led to higher heights of draw, early dilution entry, and loss of reserve (Van As, 2014). When individual drawpoints are drawn in isolation or drawpoints are spaced too wide for draw interaction to occur, then isolated draw predominates. As a result of this, the height of interaction increases, and even the flow of material is lost. In other words, the higher the interaction zone, the earlier the dilution will be encountered at the extraction level (Van As, Guest, 2020). Laubscher (1994) recommends that drawpoints should be spaced at 1.5 times the diameter of the isolated draw zone, whereas other studies (Kvapil, 1965) suggested that isolated movement zones must overlap. A follow-up investigation is being conducted to determine the optimal spacing.

From a safety point of view, widely spaced drawpoints with poor interaction resulted in overloading of vertical stress on the major apex due to the extra stagnant material and weight of the

mass from the cave. The findings by Van As and Guest (2020) concur that the loading (weight) of the overlying stagnant and compacted ore has a major impact on the stability of the apex pillar. The over-concentrated vertical stress can cause a potential shear failure between the major apex and the extraction drive underneath. Additionally, in coarse fragmentation, the stagnant material forms a barrier that prevents the lateral growth of the isolated movement zone, thus resulting in a narrow-isolated movement zone (Pierce, 2009). The argument of widely spaced drawpoints is that they improve the strength of the extraction level by creating large apex pillars that can withstand higher loads from the ore column above.

Conclusion

This study described the effect of stress, geological structures and stability of the undercut and production level on the layout design of a block cave mine. The findings of the study are summarised as follows:

- The standard guidelines for mine design cannot be given, as the rock mass properties of each mine are unique.
- Face advances perpendicular to the major principal stress and parallel to the dolerite dyke were found to be preferable.
- The mine found that a 45° lead/lag face shape of the undercut minimised abutment damage to the undercut level.
- The mine opt for widely spaced drawpoints to accommodate large LHDs, in contrast to theory, which suggests isolated draw zones, ore loss and early dilution.
- The optimal drawpoint spacing between production and ideal extraction is unknown for the geotechnical conditions at the mine.

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