Utilisation of drone technology to monitor blasting performance for the undercutting of Lift 2 block cave at Palabora Mining Company

[1]T. Chauke, [1]F.K.Mulenga, [1]V.C. Madanda, [1]N.M. Chiloane, [2]G. Mtileni, [2]M. Cloete, [2]T Lepheana, [2]D. Ntuli

[1]University of South Africa, South Africa
[2]Palabora Mining Company, South Africa

Block cave mining relies heavily on accurate blasting to provide free ore movement and avoid the unintended creation of pillars. Palabora Mining Company (PMC) utilised the cavity monitoring system (CMS) to oversee blasting during undercutting. However, the CMS system not only offers limited accessibility and line of sight, but it also produces noisy data (data with errors) with reduced accuracy. This paper investigates the use of the Elios 3 drone to monitor blasting operations and assess alignment with planned designs at PMC, while also comparing it to CMS scans. The drone, outfitted with LiDAR sensors and high-resolution cameras, conducted a survey of a 4.8 m cavity across three flights lasting six minutes each. It successfully acquired comprehensive spatial data that was converted into high-resolution 3D models using FARO and Leica Geosystems software. The results revealed significant discrepancies between planned and actual blast designs. This included instances of overbreaking, underbreaking, and unintended pillar formation, which adversely affected ore flow and mine stability. The Elios 3 drone surpassed the CMS in data quality by securely traversing hazardous areas. Furthermore, it provided accurate data, hence offering useful insights for enhancing blast execution. The drone further minimised human exposure to hazardous conditions. These findings underline the potential of drone technology to optimise blasting operations, improve safety, and extend the operational lifespan of underground mines.

Keywords: drone, block caving, blasting, undercutting, monitoring, cavity monitoring system

INTRODUCTION

Block caving is a high-tonnage underground bulk mining method particularly suited for massive, low-grade ore bodies (Rashidinejad *et al.*, 2014). It is dependent on the controlled collapse of the orebody by its own weight to permit the movement of the broken rock through draw points to the production level (Morales *et al.*, 2024). This method is very efficient and economical and is recommended for stable and strong rock masses (Moss *et al.*, 2006). However, its success is grounded in good engineering and close monitoring to ensure that the cave develops and remains stable. Undercutting is a very important step in block caving. It involves blasting a horizontal slot at the base of the orebody to initiate the caving process (Kovalenko *et al.*, 2021).

The purpose of undercutting is to prepare the rock mass in such a way that gravity can pull and move the ore with ease. The height and design of undercut play a crucial role in controlling fragmentation, ore flow and mining operation efficiency (Morales *et al.*, 2024). Bad undercutting may cause ore hang-ups, irregular cave propagation, and pillars, which are unsafe and unproductive (Xia *et al.*, 2019). Accurate blasting operations during the undercutting stage of block mine caving are necessary.

This is crucial for avoiding excessive blasting, which can result in unintentional rock fractures, unnecessary displacement of materials, and, at times, instability. Excessive blasting might also lead to greater ore dilution, damage to infrastructure, and a rise in maintenance expenses.

Insufficient fragmentation will lead to challenges in centralising all ore during the clearing process (Morales *et al*., 2024). Underbreaking, on the other hand, results in insufficient fragmentation, leaving unbroken ore behind (Kovalenko *et al*., 2021). This can result in extra secondary blasting and reduced caving efficiency by causing delays in production and increasing operational expenses. In addition to over- and underbreaking, unintended pillar formation is another common issue in block caving. The presence of these pillars can obstruct ore flow and heighten stress levels (Moss *et al*., 2006). This may ultimately lead to structural collapses or damage to machinery. Furthermore, the development of pillars may lead to a shortening of the lifespan of a mine.

Palabora Mining Company (PMC) uses the cavity monitoring system (CMS) to monitor the blasting area during undercutting. However, the CMS system not only offers limited accessibility and line of sight, but it also produces noisy data (data with errors) with reduced accuracy. Operational delays and safety risks are also common when using the system. Given these limitations, there is a need for an alternative monitoring approach that can provide higher accuracy, improved safety, and real-time insights into blast performance. While drone technology has gained traction in mining operations, its application in blasting performance monitoring for block cave mining remains underexplored.

It is in this light that the use of the Elios 3 drone is explored to monitor blasting operations and assess alignment with planned designs at PMC. The Elios 3 drone is specifically designed for confined and GPS-denied environments. It is equipped with LiDAR sensors and high-resolution cameras capable of capturing detailed three-dimensional spatial data. Therefore, the aim of this paper is to assess the effectiveness of drone technology in monitoring blasting performance during the undercutting of Lift 2 block cave at PMC.

METHODOLOGY

Study Area and its Geological Setting

This research was conducted at Palabora mine, Limpopo Province, South Africa, near the town of Phalaborwa. The mine is ranked as one of the largest copper deposits found in carbonatite worldwide. The mine has been operating since 1965 (Bezuidenhout, 2018). Palabora mine forms part of the Palabora Igneous Complex, an intrusion of carbonatite that was formed around 2060 million years ago. Within this deposit are found three main rock types, namely phoscorite, carbonatite, and banded carbonatite, all of which contain economic copper (Cu), magnetite (Fe), and rare earth elements (Gómez-Arias *et al*., 2022).

The chalcocite group of minerals, chalcopyrite, and bornite occur in silico carbonatite and banded carbonatite as the major copper minerals. There are important faults like the Southwest Fault Zone (SWFZ) and the Mica Fault, which is particularly associated with cave propagation and ore recovery at Palabora mine (Ngidi & Pretorius, 2010). The history of mining in Palabora is such that it started as an open-cast mine which reached its ultimate depth at 800 m before it transformed into an underground block cave in 2002 (Brummer *et al*., 2004). This underground operation utilises a block caving method that capitalises on gravity for breaking and moving ore at low drill and blast costs. Draw points are used for ore extraction underground, then it gets crushed and finally transported using conveyor belts for processing on the surface.

Presently, the mine produces 30,000 to 33,000 tonnes of copper ore daily for on-site processing (Sainsbury *et al*., 2016). The first block cave was named Lift 1, and it was situated beneath the crown of the open pit at a depth of 1200 m. Although caving commenced in 2004, changing from open pit to underground led to North Wall failure in the same year. This was a major slope failure triggered by the progression of the cave beyond its intended boundary. Due to the slope failure, the east side required some modifications on draw point controls, as the failure led to poor fragmentation (Richard & Sulemana, 2015; Ngidi & Pretorius, 2010). Ore flow posed major challenges because of its blocky nature within banded carbonatite (Ngidi & Pretorius, 2010). Be that as it may, Lift 1 ran efficiently for almost 20 years, demonstrating that block caving could be used on strong competent rocks (Sainsbury *et al.*, 2016). Lift 1 resources are almost depleted; however, in 2018, the development of Lift 2 was started to extend the mine's depth to 1400 m and increase its lifespan (Figure 1) (Robert Atkins Andre, 2014). Advanced monitoring techniques were introduced to prevent sinkholes and pillar collapses. The mine operates under high-stress conditions, requiring numerical analysis and earthquake monitoring. It has been noted that the development of caves in Lift 2 is much more progressive in relation to the SWFZ than the other areas and therefore poses a greater threat to surface structures (D. Sainsbury & B-A Sainsbury, 2016).

Controlled draw plans and enhanced blasting techniques were introduced for stress coping and continuous production. Palabora mine has gained international fame due to several factors, among them being its deep block caving system, complex geology and large scale of activities. Moving from open-pit to underground mining phase and continuation of construction work at Lift 2 require application of state-of-the-art surveillance technologies, including drones aimed at improving ore recovery and durability of surrounding rock mass.

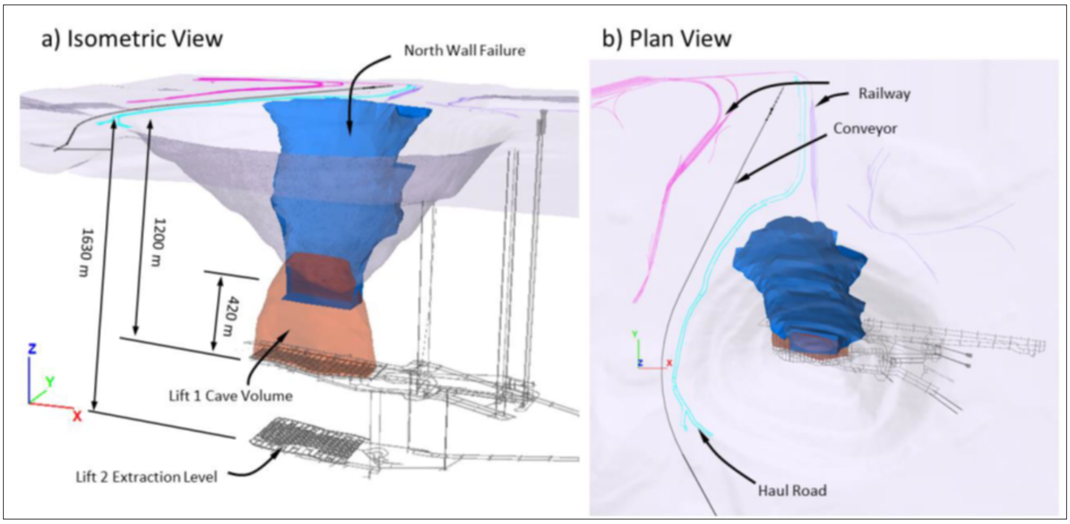

Figure 1. Isometric view and plan view of the Palabora mine, pit, Lift 1 and Lift 2 (D. Sainsbury & B-ASainsbury, 2016).

Description of the Elios 3 Drone

Elios 3 is a specialised indoor drone meant for inspection and mapping in areas where there is no GPS signal or which are too confined for GPS monitoring to work. This indoor drone is created by Flyability with features that include a protective structure which is able to withstand collisions, hence suitable for flying safely in underground mines. By using LiDAR-stabilisation-based simultaneous localisation and mapping as well as visual-inertial odometry cameras, the drone can be operated with accuracy even without reference from the GPS. This ensures real-time mapping and accurate positioning in complex environments. To ensure that it remains reliable in dangerous environments, the drone has a feature that makes it automatically return on getting a signal. The presence of advanced cameras and sensors means that this model can offer both detailed visual and 3D analysis. For the best images, it is designed with a 4000 pixels (4K) camera with a pod that can be tilted up to 180°. Furthermore, the forward looking infrared thermal camera is used for detecting hot spots or leakages. It includes a light detection and ranging (LiDAR) system that produces point clouds geo-referenced data; serving as an efficient solution for geotechnical investigations and underground mapping. Depending on the weight, it can hover in the air for between 9 and 12.5 minutes. The standard model is splash- and dust-protected (Ingress Protection 44 (IP44)), but the LiDAR payload has an IP68 rating, which means that it can be used in tough environments.

Description of the Geosight NX-150 CMS Scanner

The Geosight NX-150 CMS scanner is tough laser scanning equipment made specifically for underground mines. This scanner utilises time-of-flight) technology that helps in gathering high-precision 3D spatial data. It provides detailed scans for tunnel profiling, stope monitoring, and structural assessments with a 310° x 360° field of view and at an angular resolution of 0.1°. The scanner is connected either by wireless using WiFi or through cable, therefore easily used in various places such as mines and industries. For maximum protection against dust and water, the NX-150 has been fitted with a military-grade aluminium body and an IP65 protection rating. It can work under extreme temperatures ranging from -30°C to +60°C, thus is suitable for various underground conditions. In addition, it has a 21-volt rechargeable battery that has a long-life usage. It is compatible with laptops or tablets for data transfer and processing. It also enhances on-site calibration and provides loaner units while being repaired to ensure little or no interruption during emergency operations.

Data Collection using the Elios 3 Drone

To gather LiDAR point cloud data, the Elios 3 drone was flown into the undercut after blasting. The undercut was about 4.8 m across. Before the drone could be flown, three reference discs were placed strategically in three different areas in the undercut. These discs acted as a reference point for the drone. In the absence of any references, the total station was used to take measurements of the position of the discs or the survey prisms so that the point clouds could be georeferenced properly to the mine plan. After placing the discs or scanning the prism, calibration of the drone's LiDAR system and analysis of risks were done just before it was flown. For proper coverage of post-blast areas, the drone had to fly three times for six minutes each. The Elios 3 used LiDAR technology alongside high-resolution cameras to take images of the surrounding area. It also collected thermal as well as visual pictures for further analysis during each flight. High-resolution 3D point clouds representing the exploded regions were produced by the LiDAR sensors mapping the cavity.

Data Collection using the Geosight NX-150 CMC Scanner

A total station was used to establish control points and prisms for geo-referencing in the undercut. The undercut height was 4.8 m. Before scanning, the Geosight NX-150 CMS scanner and accessories (boom system, buggy, manual mount) were checked for correct operation. The scanner was mounted on a boom, allowing scanning inside the cavity while keeping the operator 15 m away. The scanner was connected by cable and WFi to a tablet for real-time data transfer and live viewing. Scanning was initiated remotely. The LiDAR performed a full 360° sweep, generating a dense 3D point cloud of the blasted cavity. Multiple scans were taken from different positions to minimise blind spots. Live monitoring confirmed coverage. If gaps were identified, the scanner was repositioned to capture them. Each CMS scan setup, including positioning and data capture, took about 40 minutes. After scanning, the data was geo-referenced using total station control points. The point cloud was then used for volumetric analysis and to track blast performance.

Data Processing and Analysis

Flyability Inspector 5 was used to start processing and geo-referencing Elios 3 drone LiDAR data. It begins by importing the raw LiDAR point cloud (LAS, PLY, or E57) and visual images into Inspector 5. The two types of files are aligned automatically in the Inspector 5 to create one coherent 3D point cloud. It also filters out any irrelevant data, such as those arising from either dust or reflections, before segmenting the point cloud. This is to allow for easier visualisation of important features within the mine, such as pillars and draw points, as well as voids, among others. On the other hand, GeoSight scan manager is employed for analysing raw scans of NX-150 CMS LiDAR data. The imported point cloud was cleaned by eliminating noise, reflections and distortions for better visibility. It helps in segmenting out all the features, such as the stopes, draw points, and voids. This is achieved through aligning several scans to come up with one overall underground openings 3D model.

Geo-referencing, Alignment, and Quality Control

The point cloud from the drone and CMS, after being pre-processed, was exported out for geo-referencing as well as refining the accuracy. Faro Connect was then used for point cloud registration and geo-referencing. Control points from either total station markers or surveyed reference discs help in properly doing this. This step also included coordinate transformations between UTM or mine grid systems so that all scans match the block cave mine plans with respect to relative space around them. The last step before exporting georeferenced point clouds involves quality control procedures aimed at eliminating alignment errors and reducing deviations as much as possible. The point clouds undergo further analysis in Leica Cyclone 3DR upon completion of this phase. In the same software package, the point cloud is refined and matches with the mine's coordinate system. A visual comparison is made between the scan geometry and the undercut layout to identify any anomalies. The anomalies include pillars, over- and under- breaking. Colour coding is done to show different levels of progress in drawing point excavation.

RESULTS AND DISCUSSION

To monitor the effectiveness of blasting performance in Lift 2 of Palabora block cave, the Elios 3 drone was deployed. The data indicated significant inconsistencies with the intended blast design, such as overbreaking, underbreaking, and the creation of extra pillars. It was possible to identify and describe the differences seen in the drone scans of the planned and actual blast results so as to make any necessary changes in succeeding blasting operations from this information. These figures highlight some of the differences between the actual execution and the intended blueprint of the blast taken from the drone survey.

Observations on Excessive Blasting

Figure 2 shows examples of severe overbreak observed during blasting. Figures 2a and 2b compare the planned blast perimeters with the actual outcomes. Red areas mark regions where the blast exceeded the design boundary (overbreak), while blue areas indicate underbreak—material left intact. Figure 2a reveals a serious case of overbreak: 95.6% of measurements exceeded the intended perimeter, with a maximum depth of +8.3 m. Poor blast control and likely excessive local charge concentrations are evident. In Figure 2b, 69.8% of measurements show overbreak, reaching a maximum of +3.3 m. Here, the pattern points to more localised overcharging, seen in concentrated red zones. Overbreak of this scale has major operational consequences. Large, unplanned voids can accelerate cave propagation and undermine rock mass stability. They also increase the demand for secondary ground support, raising both cost and risk. Comparing the planned and actual blast profiles helps pinpoint performance issues and guide corrective action. Consistent, precise blast design and close monitoring are critical to improving control and reducing unplanned overbreak.

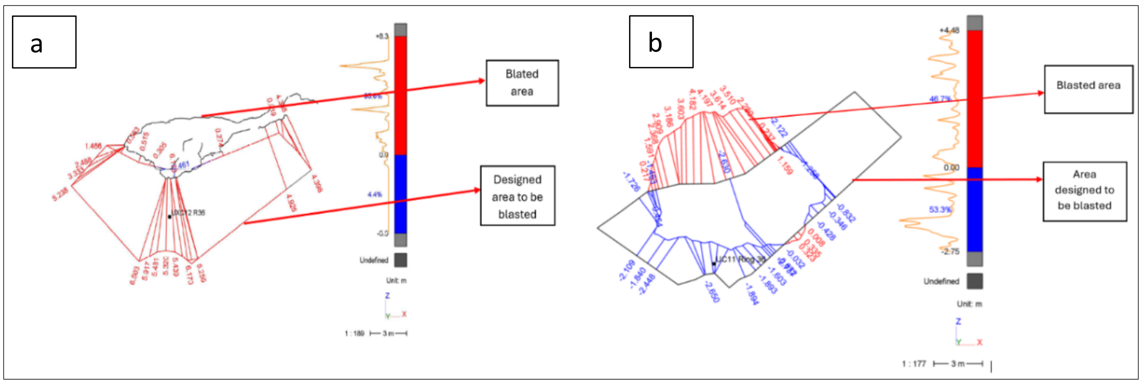

Figure 2. 2D sectional views of over-breaking from drone scans (a, b).

Under Breaking Effects

Figure 3 (a,b) compares the drone scan images for planned (blue) and actual (gold) blast areas; it highlights the level of underbreaking for this case. Figure 3a identifies areas at the bottom where there is a clear underbreak, as seen by large intact sections. On the other hand, the upper part has managed to experience some form of material breakage with little effect on the lower part. Figure 3b also proves that there was underblasting in some of the areas. It is clear that underbreaking occurred between points R39 and R43. This indicated that the applied energy was inadequate to break the rock mass (Yang *et al.*, 2024). However, failure of blast design to consider changes in rock strength, inclusive of if there was under-optimisation in hole spacing, burden, or charge distribution, could make the design a secondary issue also. Even though there is effective breaking at some points, most of the rock parts are non-fragmented. This may cause blockages in orebody propagation. Therefore, there will be challenges in recovering ore and the possibility of creating strong non-caving pillars.

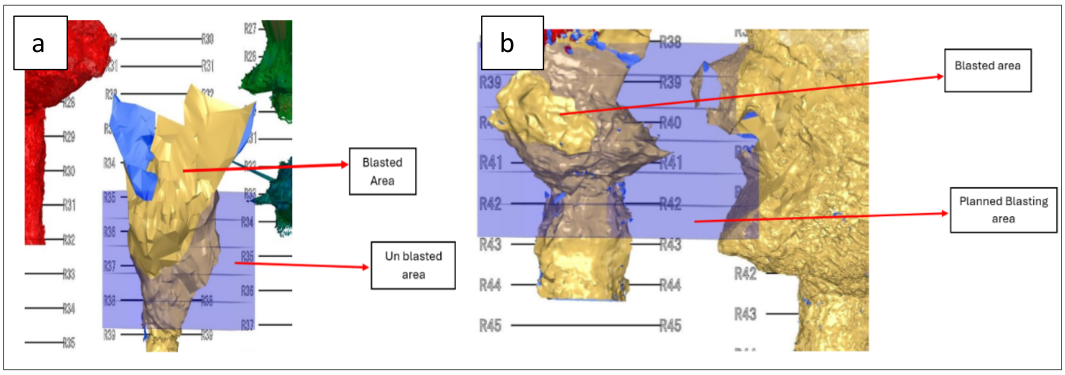

Figure 3. Comparison of blasted areas vs planned blasting zones and ring design from a drone scan (a, b).

Pillar Formation

Unblasted rock masses create pillars that prevent a continuous caving phase. Figure 4 indicates many areas where pillars are forming. A lack of sufficient blast energy or the blast design has led to unbroken rock and the presence of multiple evenly spaced pillars. The pillars can be identified near rings R31, R32, and R35 in Figure 4. A large pillar can also be observed on the right side of the figure under UCX11. Ore recovery, surrounding rock strength and overall cave formation efficiency may be affected by unintended pillars. Broken ore which may be unable to move freely in its natural path due to these pillars results in draw point blockages. In addition to this, they lead to uneven distribution of stress, thereby increasing chances of local collapse or seismic activities (Linzer *et al.*, 2021). Solid pillars also disturb the formation of caves, making it necessary to use more explosives during blasting (Gams, 2023); thereby incurring higher annual expenses with subsequent time overruns.

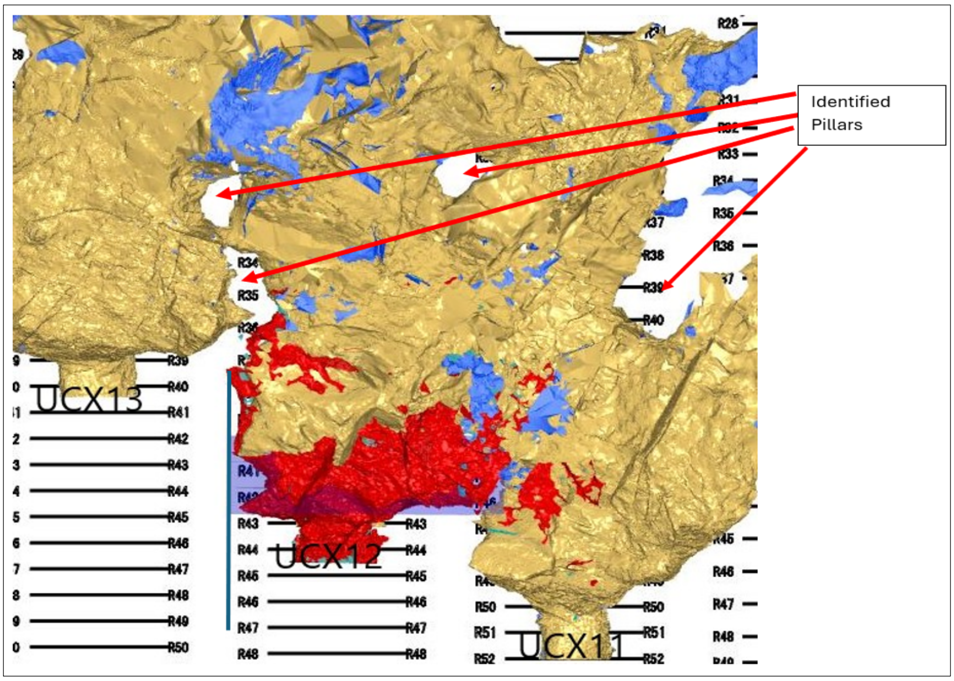

Figure 4. Identified pillars and unbroken rock from the drone scan.

Comparison between Elios 3 Drone and Traditional CMS Monitoring

In Figure 5(a), the lower red scan shows the drone-derived point cloud. The upper green scan represents the CMS data. Both are superimposed on the planned undercut geometry to enable spatial comparison of coverage and depth penetration. Figure 5(b) isolates the drone scan and overlays it with the undercut and ring designs. The scan shows strong alignment with the planned geometry in both volumetric extent and shape fidelity. Figures 5(c) and 5(d) compare CMS scans to the ring and undercut designs respectively, illustrating the CMS's more limited volumetric coverage and more fragmented representation of the blasted volume. The drone data is denser and more continuous, particularly in capturing complex blasted voids. CMS scans cover a narrower zone, limiting interpretability in some areas. This distinction is critical when evaluating the accuracy and completeness of post-blast volumetric models.

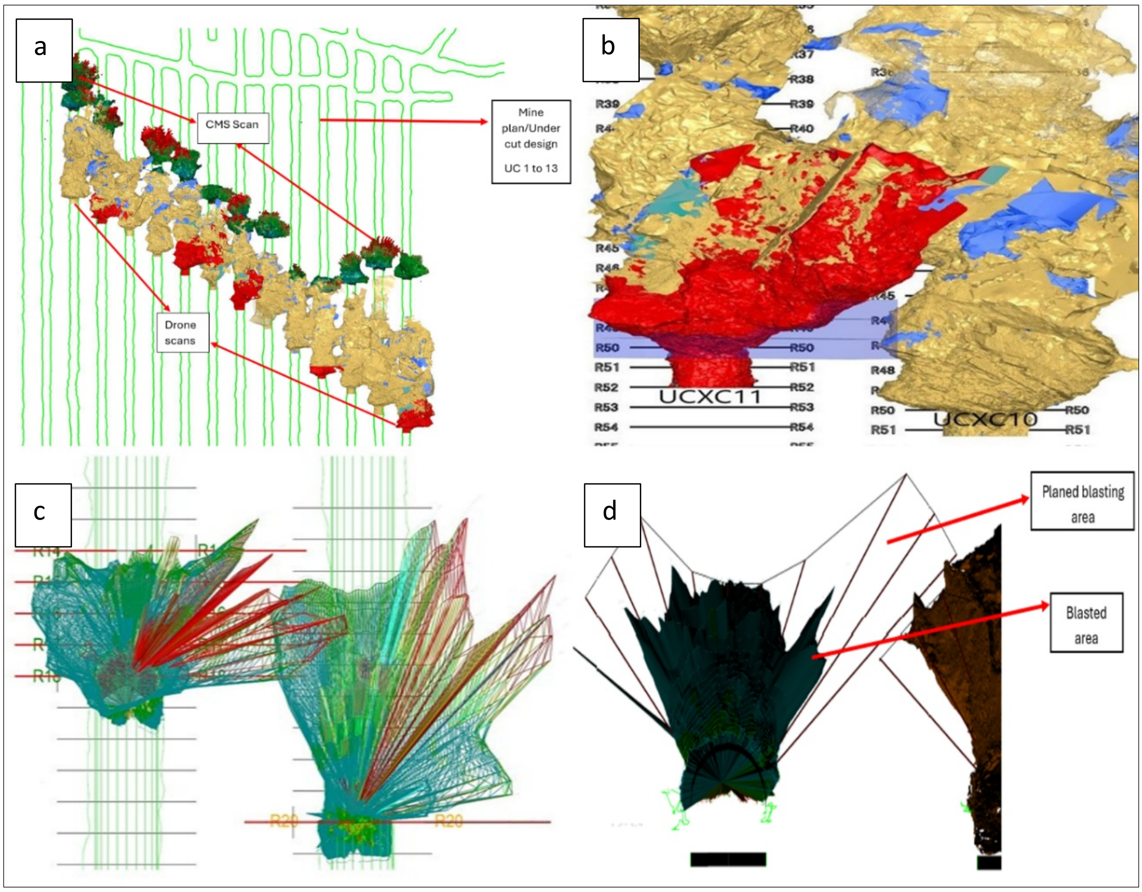

Figure 5. Comparison of CMS and drone-based scanning results against undercut and ring design plans. (a) Combined visualisation of mesh models generated from drone and CMS scans, overlaid on the planned undercut geometry; (b) Visualisation of drone-derived mesh compared to the planned undercut and ring designs; (c) and (d) Visualisation of CMS scan meshes compared to the planned undercut and ring designs. Different mesh colours are used for visual distinction only and do not represent material type or data source.

Comparison between Elios 3 Drone and Traditional CMS Monitoring in terms of Safety

Safety is one area where the Elios 3 drone offers clear operational gains over CMS scanning in the Lift II block cave undercut. CMS scanning requires the operator to work within 15 m of the cavity. Each scan takes about 40 minutes, during which the operator remains exposed to geotechnical hazards. It also requires drawpoints to be cleared to at least 50% post-blast to allow scanner access, delaying scanning and increasing downtime. The static position of the CMS causes shadowing in the scan data. The drone removes these constraints. It is flown remotely, with the operator positioned 15 to 50 m away, outside the hazard zone. Drawpoints do not need to be cleared before scanning. A typical flight takes six minutes, with scanning and data capture finished in under 15. Operator exposure is reduced by an estimated 70–80%, based on both time and distance. The drone's mobility also reduces shadowing, producing more complete point clouds. Drone operation requires basic pilot training and knowledge of site safety protocols. CMS scanning demands more specialised training to safely position and operate the equipment in confined, hazardous areas. The lower risk exposure and simpler training requirements make drone-based scanning well suited for frequent blast monitoring in block cave operations.

CONCLUSION

This study assessed the use of the Elios 3 drone for monitoring blast effects during undercutting of the Lift II block cave at Palabora mine, with a direct comparison to conventional CMS scanning. The aim was to evaluate the effectiveness of drone-based scanning in capturing post-blast cavity geometry, identifying deviations from design, and supporting blast performance assessment. The Elios 3 drone produced high-resolution 3D mesh data that allowed for detailed evaluation of overbreak, underbreak, and pillar formation. The results showed that overbreak reached up to +8.3 m in some areas, increasing the risk of cave instability and contributing to potential dilution. Underbreak was also observed, particularly between levels R39 and R43, where insufficient blast energy left intact rock in the drawpoint zone. This resulted in the formation of unintended pillars, clearly visible in Figure 4, particularly near R31, R32, R35, and beneath UCX11. Such pillars obstruct ore flow, increase the likelihood of drawpoint hang-ups, and raise operational risks due to stress redistribution and potential seismic activity. The Elios 3 drone provided superior scan coverage compared to CMS, reducing shadowing and allowing full mapping of complex cavity geometry. Importantly, drone-based scanning required no drawpoint cleaning and reduced operator exposure time and distance, improving both safety and operational efficiency. CMS scanning was slower, required extensive setup and cleaning, and produced more limited data. Accurate monitoring of blasting outcomes is essential for optimising cave performance and managing operational risk. Based on the findings of this study, the Elios 3 drone is recommended for routine blast performance monitoring at Palabora mine. Its advantages in data coverage, scanning efficiency, and operational safety make it a preferable tool for this application compared to conventional CMS scanning.

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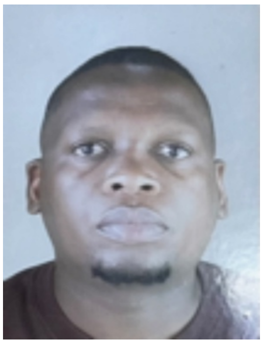

Tebello Lepheana
Survey Supervisor(underground)
Palabora Mining Company

I'm Tebello Lepheana, a Mine Surveyor based in Evander, Mpumalanga, with over 15 years of experience in both underground and open-pit mining. My career has been built on a mix of hands-on surveying, leadership in survey operations, and adopting new technologies like 3D laser scanning and drone-based underground mapping. I've always believed that accurate, efficient survey work is the foundation of safe and productive mining, and I've made that my focus throughout my career. I started off as a Learner Surveyor at Concor Mining, where I got my first real taste of the mining environment. From there, I joined Evander Gold Mines, where I worked for a full decade. That's where I really cut my teeth—leading underground surveys, setting out mining layouts, and making sure that every line, peg, and measurement helped the mine run smoothly. When the mine eventually closed, I knew I had to grow further. Over the years, I've taken on roles that pushed me to grow technically and personally. At Leviking Technical Services, I managed pit surveys and drill designs. Later, I moved into a Mine Surveyor role in the DRC with Alphamin Bisie Mine, handling underground survey work before COVID brought things to a halt. That break didn't slow me down for long. I joined Dwyka Mining Services and worked on some exciting projects using 3D scanning, point cloud modelling, and the Blast Gyro system. I loved working with new tech seeing how data could shape smarter mining and I supported projects all over Africa. Right now, I'm working as a Supervisor Survey (Underground) at Palabora Mining Company. I lead a strong team, oversee underground drone scanning, manage survey data processing, and ensure our work meets safety and compliance standards. Training and mentoring junior surveyors is a big part of what I do, and I take pride in helping others grow. I've earned a National Diploma in Mine Surveying from UNISA, and I also hold several certifications from the Chamber of Mines. I'm a registered member of the South African Geomatics Council, and fluent in multiple South African languages, which has always helped me work across different teams and regions. If there's one thing that defines my approach, it's the belief that technology and experience should work hand in hand. Whether it's using drones for underground scans or turning raw data into actionable insights with tools like MicroStation and Cyclone 3DR, I'm always looking for ways to improve and modernize the way survey work is done. Looking ahead, I want to keep pushing boundaries taking on more leadership, more innovation, and ultimately contributing to mining operations that are not only productive but safer and smarter too.