Interaction between the block cave and the pit slopes at Palabora mine

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Synopsis

The Palabora Mining Company has successfully extended the life of its operation by developing a 30 000 tpd block cave underground mine below the now closed open pit. The process of transitioning from surface to underground mining has been technically, operationally and managerially challenging. This has been due to a number of factors, in particular, the development of a block cave in a very competent rock mass. The competence of the rock mass is clearly demonstrated in the open pit that preceded the block cave, one of the steepest deep open pit excavations in the world. With cave breakthrough, however, the pit was 'instantaneously' deepened by 400 m causing a major failure of the north-west wall involving close to 100 Mt of waste material.

Introduction

The Palabora Mining Company has successfully extended the life of its operation by developing a 30 000 tpd block cave operation below the now closed open pit. The process of transitioning from surface to underground mining has been technically, operationally and managerially challenging. This has been due to a number of factors, in particular the development of a block cave in a very competent rock mass with limited experience within the industry on which to base design. In effect Palabora was 'pioneering' a difficult position in any operation. However, with planned production rates in excess of 30 000 tpd; Palabora has successfully transitioned from an open pit to an underground operation and is considered to be at the cutting edge for this type of development.

There were a number of important achievements during the transition process. These include:

- Safety performance during construction and operations comparable with open pits
- Caving of a competent rock mass.
- Development of the 'crinkle' undercut
- Taking secondary breaking to new levels
- Highest lift heights yet attempted in a block cave
- One of the fastest production build-ups among block cave operations
- Ramp scavenging in the pit concurrent with cave development.

Equally important were the lessons learned:

- The need to enhance geotechnical knowledge, including data collection, ground characterization and analysis of rock mass behaviour
- The limitations of the various tools currently available to reliably predict cave performance
- The critical importance of quality and performance monitoring
- The impact of a large pit on the water management strategy
- The interaction between the cave and the overlying pit.

The last lesson was brought into focus when, shortly after cave breakthrough, cracking was observed some 250 m behind the north-west wall of the pit. With time, what initially appeared to be two separate wall failures coalesced into a single failure involving some 100 Mt of material over the full wall height. The failure has highlighted a deficiency in our understanding of the effect that caving has on pit wall stability and, equally important, the impact of the failure on cave operations.

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Overview

Project description and history

The Palabora Mining Company (PMC) was founded in 1956 and open pit mining operations commenced in 1966 at rate of 30 000 tpd increasing to 82 000 tpd prior to closure in 2002. In total some 960 Mt of ore and 1 300 Mt of waste were mined. Throughout pit operations there was a history of innovation and optimization, for example the use of trolley assist for 240 t haul trucks and the introduction of in-pit crushing. The pit was approximately 800 m deep with inter-ramp slope angles ranging from 37° in the upper weathered lithologies to about 58° in the competent constrained ground toward the base of the pit (Figure 1).

The orebody is an elliptical shaped vertically dipping volcanic pipe measuring 1 400 m and 800 m in plan with resources to 1 800 m below surface. Transgressive and banded carbonatites form the central core of the orebody with the banded carbonatites and transgressive carbonatites dominant in the western sector and eastern sectors of the orebody, respectively (Figure 1). Barren dolerite dykes with a steeply dipping north-east trend are present as are a number of north-west and north-east trending faults.

The development of a 30 000 tpd block cave operation was approved in 1996. Shaft construction started in 1997. Target production was achieved in May 2005.

The production level, Figure 2, is located approximately 1 200 m below the surface and approximately 400 m below the final pit bottom while the production footprint, consisting of 20 cross-cuts is 650 m long and approximately 250 m wide. Drawpoints are on an off-set herringbone style. The undercut level is located 18 m above the production level. LHDs dump directly into four crusher stations located along the northern extremity of the production footprint. Access to the orebody is via a 10 m diameter service shaft. Ore is hoisted through a 7.5 m production shaft equipped with four 32 t skips.

Palabora has the highest lifts yet attempted ('lift' is the vertical distance from the production level to the break through point on surface or in the open pit above). This points the way for future block caves. High lifts allow a substantial reduction in capital requirements per vertical ton of ore mined.

Key statistics on the underground are given in Table I. A detailed description of the mine layout is given in Calder *et al.*, 2000, while additional data on cave progression are given in Moss *et al*, 2004.

In 2004 the underground mine had achieved one of the best safety records for an underground operation anywhere in the world. Today with construction complete, the LTIFR rate is 0.50, competing well not only with underground mines but also with surface operations. This is a notable achievement for both Palabora and Rio Tinto.

Cave development

The Palabora orebody is the strongest rock mass in which block cave mining has been attempted and there was considerable scepticism within the industry as to whether it would cave effectively. The Palabora orebody is caving and caving well.

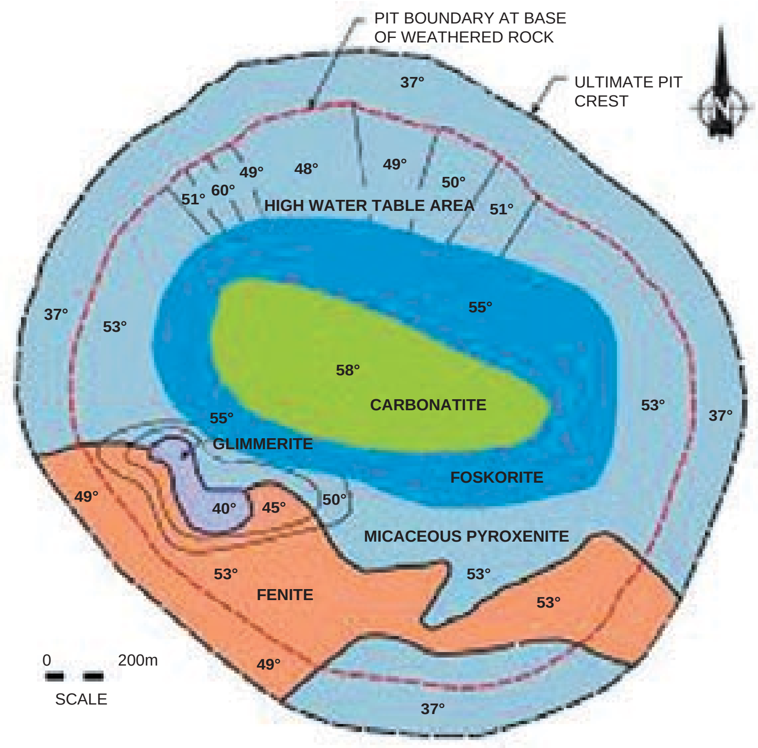


Figure 1—General geology and pit slope geometry

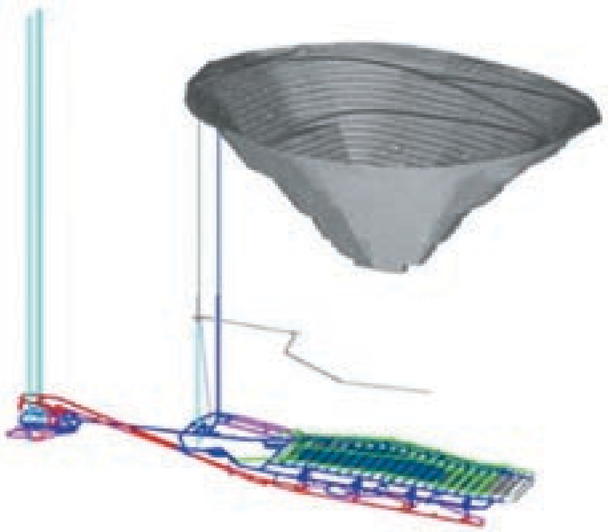


Figure 2—Plan of production level showing dykes and faults

Table I

Summary statistics

Rock mass quality (Q')	10–15	Hydraulic radius at which caving initiated	45 m
Lift heights	400–600 m	Estimated swell factor	20%
Number of production cross-cuts	20	Number of drawbells	166
Drawbell dimensions	34 by 17m	Average draw rate (May 2005)	116 mm

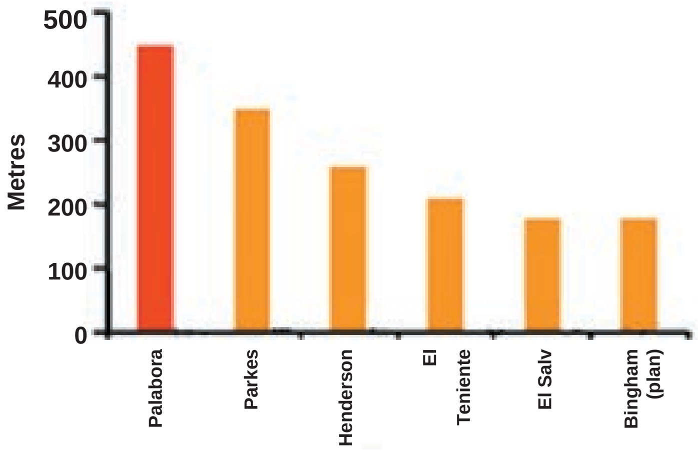


Figure 3—Comparison of lift height

Undercutting (the process used to horizontally slot the orebody and initiate caving) started in 1999 and was highly successful. The undercut was advanced ahead of construction of the production level to providing a 'stress sheltering' for the excavation of the production level. Palabora was the first block cave to use the 'crinkle cut' undercut design. The combination of geometries proved to be an extremely efficient undercutting method taking 52 months to undercut 119 000 m^2 at rates reaching some 4 500 m^2 per month.

During feasibility it was predicted that caving would be initiated when the undercut area reached 140 m by 140 m. It was recognized that due to lack of knowledge there was substantial uncertainty with this prediction but that the dimensions of the overall footprint were sufficient to cater for this uncertainty. This was borne out by experience as, although the dimensions required to initiate caving were about 30% greater than that predicted, the hyrdaulic at which caving occurred was well within the dimensions of the production footprint. Caving initiated in April 2002 when a hydraulic radius of 45 was reached.

A number of monitoring systems including TDRs, open holes and a mine wide micro-seismic system were installed to track cave propagation. Of these, only the micro-seismic system provided a broad view of cave progression (see Glazer and Hepworth, 2004). By locating events, it was possible to determine when caving was initiated, when the pillar between the cave back and pit floor failed and to track stress transfer that occurred as a result of the caving process. The micro-seismic system has also provided important information on pit wall behaviour.

As expected, the strong competent rock mass initially resulted in coarse fragmentation with secondary breaking being a major challenge. No cave operation has undertaken the amount of secondary breaking that has been required at Palabora, where some 50% of the initial tonnage has had to be blasted to clear drawpoint hang-ups and blockages. Although coarse fragmentation was anticipated, the ore has actually broken finer than anticipated; the process of safe and efficient clearing the hang-ups has required substantial organizational effort. In doing so, however, the mine has achieved some notable technical successes:

- The development of secondary breaking equipment from prototype through to production units, including the considerable learning process that typically occurs with new equipment
- Development of effective industrially engineered secondary breaking processes that fully utilize available resources.

The cave is now fining with increasing height of draw. This will result in increased draw rates and production performance.

Transition issues

A number of issues were encountered during the transition from an open pit to an underground operation. These included a culture change from surface to underground mining, down-sizing of the mine work force in recognition of reduced throughput and the availability of appropriate skills. Technically, the three most important transition issues were the production shortfall that occurred with pit closure, water management within the open pit and cave pit interaction.

Ramp mining

PMC realized that underground production would not be sufficient to sustain milling and smelting operations once pit operations ceased. The decision was made to augment production with ramp mining operations. This involved mining the pit ramp in a series of small benches (5 to 7 m high) effectively increasing ramp gradient from 10% to 15% (for more details see Whitham *et al.* 2004). Over a 20-month period some 10.4 Mt of ore was mined in this manner at production rates averaging 16 000 tpd.

From the outset, detailed geotechnical input was a key aspect in the design and successful implementation of ramp mining. One of the key factors controlling the mining sequence was determining where in the pit scavenging could safely be undertaken, given that the cave was propagating upwards toward the pit floor. The size of the crown pillar buffer zone (the vertical distance measured from the top of the cave to the lowest elevation in the pit where mining could be safely carried out) was set at 200 m. This distance was based on an assessment of the stability of the web of ground between cave back and pit floor. Following on from the initial investigations, day-to-day geotechnical management was maintained throughout the project, comprising:

- Monitoring by survey prisms, inclinometers and geophones
- Regular inspection of pit walls
- Direction of remedial shotcreting
- Approval of all blast designs
- Inspection and geotechnical clearance after each blast.

Water management

The open pit provides a large catchment area (240 Ha), funnelling surface run-off down into the underground mine via the cave. The average annual rainfall is 534 mm with the majority of the rains falling during the months of December through January as major storm events.

At feasibility, it was considered that storm run-off would be substantially attenuated within the cave, releasing floodwater at a rate that could be managed by the underground pumping system. The mine pumping system was designed accordingly. However, experience with actual storm events has shown that storm water reports underground rapidly (in less than 12 hours) indicating that the cave material has a hydraulic conductivity of around 10^{-2} m/sec, several orders of magnitude greater than originally estimated. Thus, it was realized that a significant deficit existed in the water-handling capacity of the underground mine. There would be times when the underground pumping system and water storage facilities as designed would be unable to cope with the stormwater inflows and sections of the mine would flood.

In order to predict the probability of flood events, a series of simulations was carried out using the history of storm events in the region. Stochastically generated rainfall data were used to simulate rainfall as a variable flux on the model surface. The results of the rainfall analysis show that the worst case event of a 1:100 year storm in 24 hours has a 2% probability of occurring within the next 18-months and a 10% probability of occurring within the next ten years. This level of storm would deliver 644 000 m^3 of water into the open pit and would cause substantial flooding of the underground mine. Different stages of mine life were examined together with options for water management, including:

- Increasing interception of rainfall in the pit.Creating underground water storage
- Minimizing recovery times from a major flood by the purchase of key capital spares to facilitate recovery
- Establishing an ‘insurance stock’ of concentrate.

The analysis resulted in the following water management strategy:

- Installation of pit sumps of sufficient capacity (325 000 m^3) to contain 60% of the projected inflow
- Installation of water tight doors on the return air way system to provide 70 000 m^3 of emergency storage.

This strategy was followed. However, the failure of the north-west wall changed the geometry of water flow into the underground workings. Although the failure removed one of the most productive pit sumps, it is considered that the failure itself provides very substantial storage. To date, the mine has been able to comfortably handle all storm events.

Cave-pit interaction

There has been interaction between the pit and the cave. Initially, the impact of the pit on the cave was to concentrate stress within the web of ground between pit floor and cave back. The increased stress level aided cave propagation by causing existing fractures to extend and creating new fractures. More importantly, this process has affected primary fragmentation and substantially reduced the secondary breaking requirements.

Conversely, the cave has affected pit wall stability. Movement of all pit walls increased substantially upon cave breakthrough into the bottom of the pit. The greatest amount occurred in the North Wall where cumulative movements of in excess of 1.5 m were measured. The first indication of a major problem, however, was a bench failure adjacent to one of the pit sumps. This was followed by the discovery of large cracks some 250 m back from the pit rim (note: it is not known if the cracking occurred before or after the initial bench scale failures as only once the failure occurred was a survey made of the dense bush that surrounds that potion of the pit).

The failure grew in size until after a period of about 18 months it encompassed a major section of the North Wall with the crest some 50 m back from the pit rim and the toe somewhere near the original pit floor. The failure dimensions were some 800 m high by 300 m along the wall, see Figure 4. The depth of the failure can only be surmized, but the rim is thought to be reasonably shallow, about 50 m thick.

The failure affected several segments of the mine's infrastructure including access and haul roads, tailings, water and power lines, water reservoirs and a railway line. Fortunately, it developed at a relatively slow rate allowing the various facilities to be moved prior to the ground on which they were located become enveloped in the failure.

There was concern for other major facilities including the ventilation shaft, located on the East Wall within the pit and the production and service shafts located some 90 m from the rim of the East Wall. Thus, an extensive monitoring programme consisting of a network of GPS stations, tiltmeters and crack meters was initiated, augmenting the original pit system and the cave micro-seismic system. This was followed by a comprehensive programme of numerical modelling of cave pit interaction (see Brummer *et al.*, 2006 for a detailed discussion on the failure and the modelling process). The modelling results, once calibrated against the monitoring, indicated that the failure was associated with pervasive jointing and the very significant stress change that occurred during cave breakthrough.

From the surface monitoring results three distinct movement zones were identified. As shown in Figure 5, there appears to be a strong relationship between these zones and seismicity. Not surprisingly, a direct relationship between movement of the failure and the amount of material drawn from the cave was observed.

The angle from undercut level to the surface limit of cracking is about 55°. This shallow angle was not anticipated in the strong competent rock mass forming the walls of the pit. Analyses of cave pit interaction were carried out as part of the feasibility study. The results of these analyses were reviewed both internally and externally. The conclusion reached was that the developing cave would induce failures of sections of the pit wall, but that these would be contained within the footprint of the pit. In part, this underlines the limited knowledge of caving-induced subsidence, particularly in combination with a deep steep pit traversed by major structures.

The failure also has the potential to affect underground production. The majority of the failed rock is significantly below cut-off grade. As the cave is pulled, this waste material may move at a faster rate than the ore due to differences in size between caved ore and the failed waste. This could result in premature dilution ingress and shortening of the mine life. Work is underway to study this phenomenon with the aid of both physical and numerical modelling.

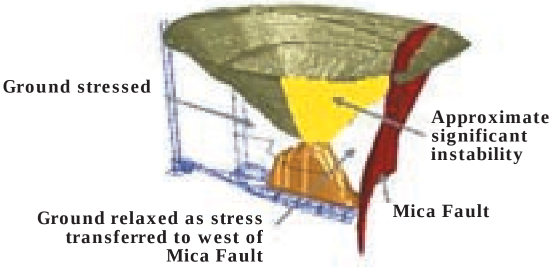
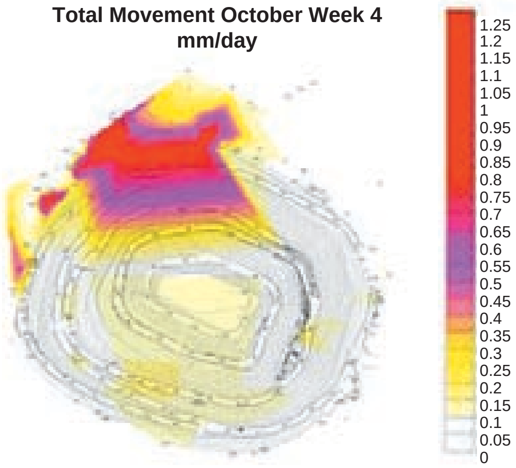


Figure 4—Zone of slope instability



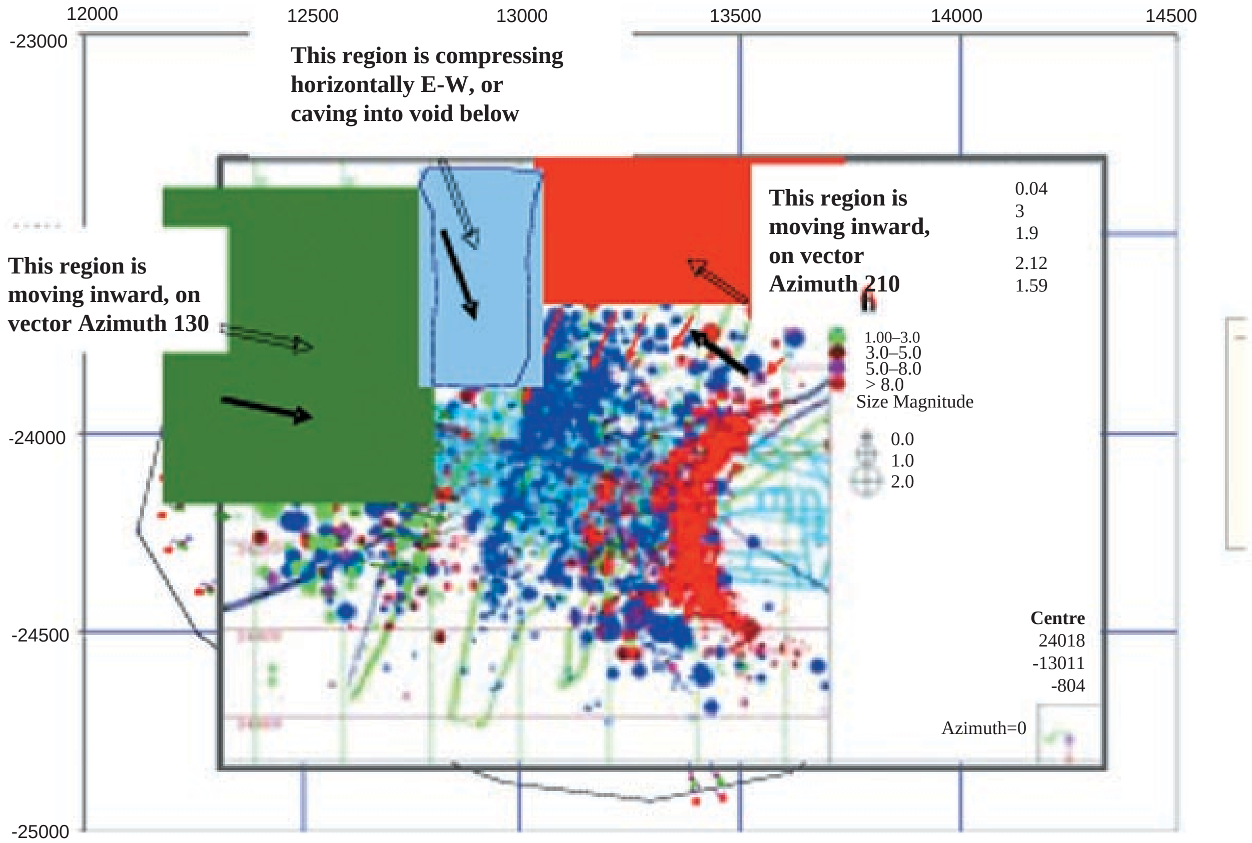


Figure 5—Movement zones and seismic activity

Conclusions

Palabora Mine has transitioned from an open pit to an underground project to a block caving operation with production having reached the targeted rate of 30 000 tpd. A number of firsts have been achieved during this transition process:

- Successful caving beneath one of the deepest and steepest pits in the world
- Successful ramp scavenging above an active block cave
- Successful development of a high lift cave
- Development of methods to effectively secondary break in excess of 50% of drawn tonnage.

Several major lessons have been learned:

- Block caving can be a viable method of prolonging mine life
- However, cave pit interaction, in particular the complex interaction between induced stresses and structure that occurs during cave progression and breakthrough, is poorly understood, resulting in poor prediction of rock mass performance. Given the level of up-front investment in a block cave, it is extremely important to develop reliable predictive tools
- The permeability of coarse caved ground is high and must be catered for by appropriate water management.

Acknowledgements

The paper is the result of all those who participated in the Palabora Underground Mine Project and the role of the authors has simply been to report this work to a wider audience.

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