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Early experiences from the Grasberg block cave: A rock mechanics perspective

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Abstract

As the Grasberg open pit is completed in 2019, the underlying Grasberg Block Cave (GBC) will rapidly mature as a primary source of production at PT Freeport Indonesia operations, supplementing the Deep Ore Zone (DOZ) and Deep Mill Level Zone (DMLZ) caves. After years of planning, development and revisions to the extraction strategy, early information on footprint rock mass response to undercutting and the nature of caving is now available to confirm or guide adjustments to strategy. Despite the early stage of mining, much has been learned regarding cave propagation, fragmentation, stress states, pillar stability and ground support performance. This paper provides a timely rock mechanics focused update from one of the largest planned caving mines in the world.

1 Introduction

At the time of writing, the maturing Grasberg Block Cave (GBC) is producing an average of 14,500 tpd from three active mining fronts. The mine is currently comprised of approximately 250 km of development with 42,000 m^2 of established undercut from two production blocks beneath the Grasberg open pit. The pit to underground transition is ongoing under strict geotechnical control with a separation of approximately 175 m. Pit operations are expected to cease by the end of 2019 with breakthrough of the cave to pit in mid-2020.

Heterogeneous geology and stress conditions have produced a varied rock mass response across the mine footprint. The strategy to manage this response during rapid undercut advance has considered local experience in past/current caves (DOZ, DMLZ), industry experience from other caving operations and numerical modelling forecasts. Cave management guidelines and engineering control measures are documented within the GBC Cave Management Plan (CMP). The CMP provides guidance on a number of operational criteria including lead-lags, undercut front length, draw/cave angle and draw rates. Ground control practice is governed by the Ground Control Management Plan (GCMP). Both the CMP and GCMP will be referenced throughout this paper as they each play critical roles in maintaining a safe and operationally effective mine footprint.

Results gained on cave and footprint performance to date, as well as forecasts of expected deformation and caving milestones, have been used to maintain, update and audit the management criteria. A sample of prominent criteria are rated based on their currently perceived importance to the GBC operation.

2 GBC mine overview

Figure 1 illustrates the current GBC cave back geometries with life-of-mine height of draw (HOD). Column heights range from 250 to 550 m with extraction of stated reserves scheduled to run through 2041. Major and minor pillar extraction level pillar spacing is 30 and 20 m, respectively.

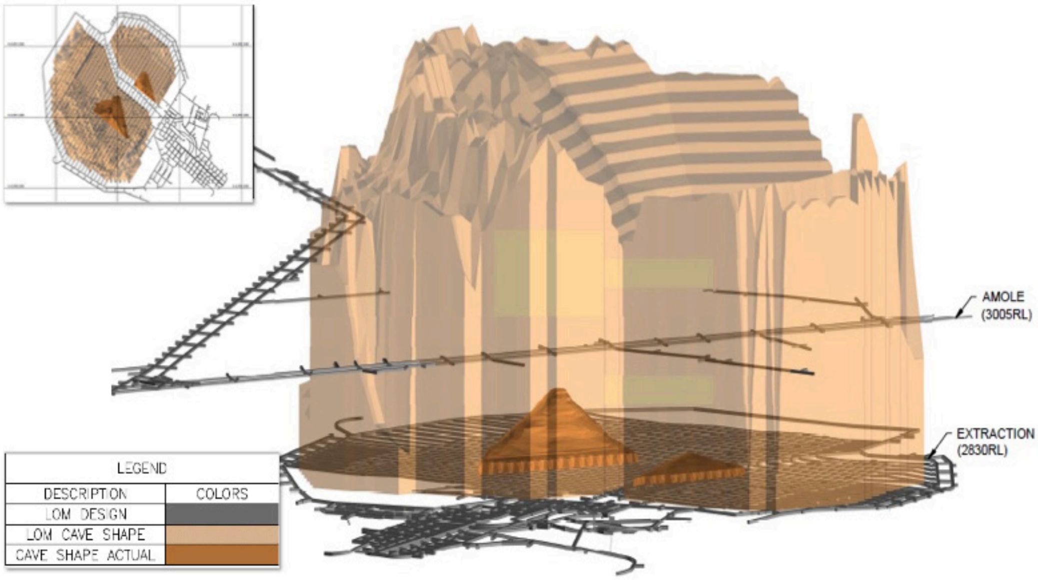

Figure 1 Height of draw (HOD) with current cave back geometries (clipped to final Grasberg pit shell)

Undercutting in Production Block 2 South (PB2S) was initiated in late 2018, while Production Block 1 South (PB1S) undercutting began in early 2019 (Figure 2). Production Block 2 North (PB2N) undercut was initiated in mid-2019 forming a unified cave with PB2S. As of October 2019, both the undercut and caves have grown significantly with sustained caving achieved at a hydraulic radius of approximately 39 and 27 for PB2 and PB1S, respectively.

The dominant rock type in PB2 and PB1S is diorite and to a lesser extent, andesite and breccia. The diorite is typically massive to semi-massive characterized by poorly developed jointing and moderate vein intensity. The mean intact strength of the diorite is approximately 110 MPa (Campbell et al. 2018). Field and laboratory observations at the GBC have recently shown that veining plays a key role in rock mass strength reduction (Bewick et al. 2019). Scaled rock mass strength (tunnel scale) estimates conducted via the synthetic rock mass (SRM) approach yield a scaled strength in the range of 25 MPa (Pierce et al. 2020). Prominent geotechnical domains with current as-built extraction level development are shown in Figure 2. An estimated stress path through pre-mining, abutment and cave load stages for a sample extraction level pillar is shown in Figure 3.

3 Ground support and pillar performance

Prior to undercutting, a number of mine-scale design changes were implemented based on an improved understanding of geological and stress conditions (Campbell et al. 2018). Specific to the undercut and extraction levels, changes focused mainly on undercut and development sequencing, the prioritisation of various blocks within the footprint and the transition from pit operations. With excavation designs and sequencing optimized for PB2 and PB1S, attention turned to ensuring footprint deformation is managed through robust ground support and proactive ground rehabilitation. Early observations of ground support systems and pillar performance are now available.

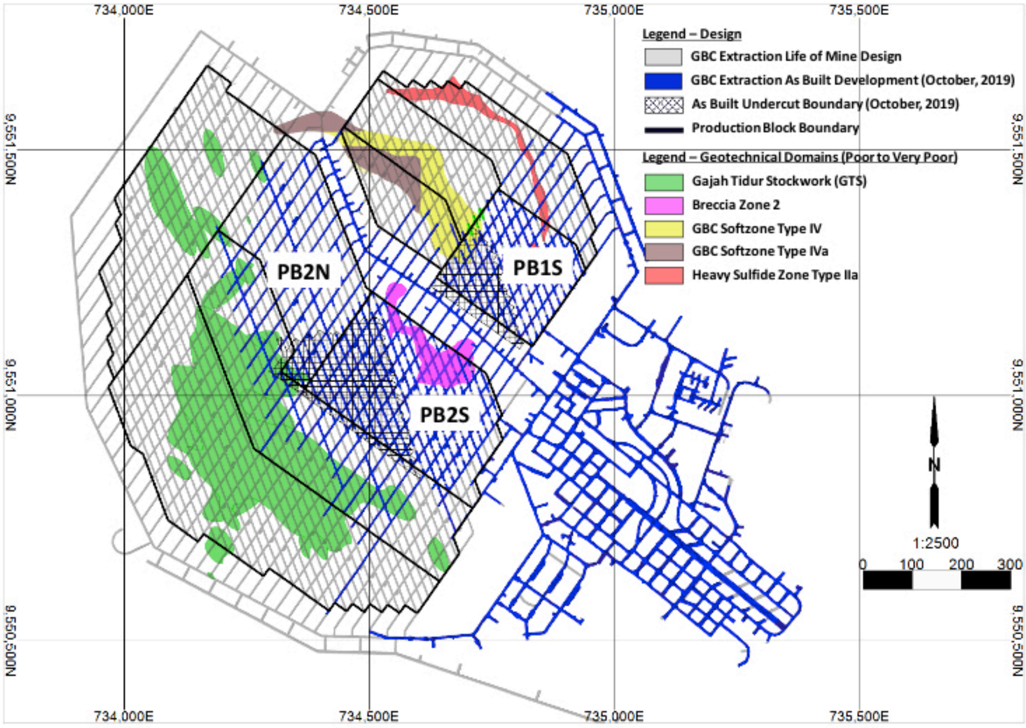

Figure 2 Current undercut status with "Poor" and "Very Poor" RMR geotechnical domains (note that the unshaded portions of PB_2 and PB_1S are predominantly competent diorite and andesite)

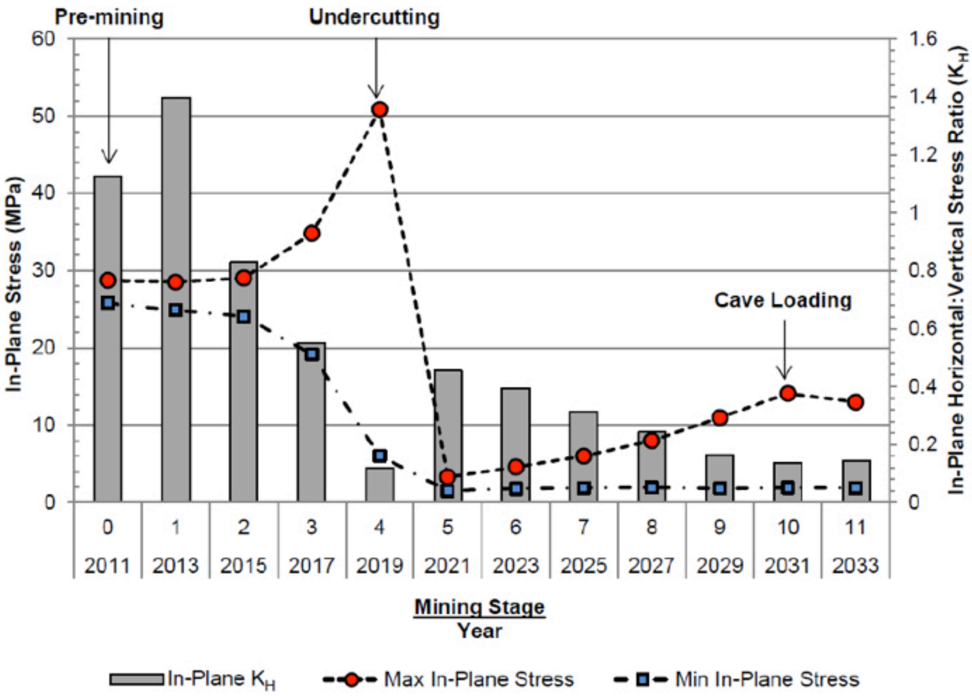

Figure 3 Generalized loading path within the GBC footprint (2830 RL extraction level; after an internal report issued to PTFI). The plotted KH>1 when the major in-plane stress approaches horizontal (< 45˚ from horizontal) and KH < 1 when the major in-plane stress approaches vertical (> 45˚ from horizontal)

3.1 Ground support

Ground support installed within the GBC footprint is designed to provide a safe production environment during the undercutting process and subsequent production periods. Beyond the standard design considerations, the following aspects are considered when defining ground support systems on the GBC footprint:

- undercutting methodology (pre, advance, or post)
- undercut sequence, advance rate (with bell construction rate) and lead-lags
- anticipated pillar instability modes (e.g. bulking, shear failure)
- location and sequencing of in-panel facilities (grizzly, rock breaker stations, ventilation raises, etc.)
- thickness of undercut and extraction level sill pillar

Although each design is evaluated on a case-by-case basis through a multistage approval process, standard ground support designs have been established to cover typically encountered conditions. Design standards for exaction and undercut level ground support for "Fair" to "Good" rock mass (RMR) and stress conditions are shown in Figure 4. Non-standard designs including steel sets and full circumference liner systems are issued on an as-needed basis. To maintain drive integrity where strain and/or corrosion impact reduce ground support capacity, additional support elements are added via a Preventative Support Maintenance (PSM) schedule. An example PSM schedule for the GBC extraction level is shown in Table 1.

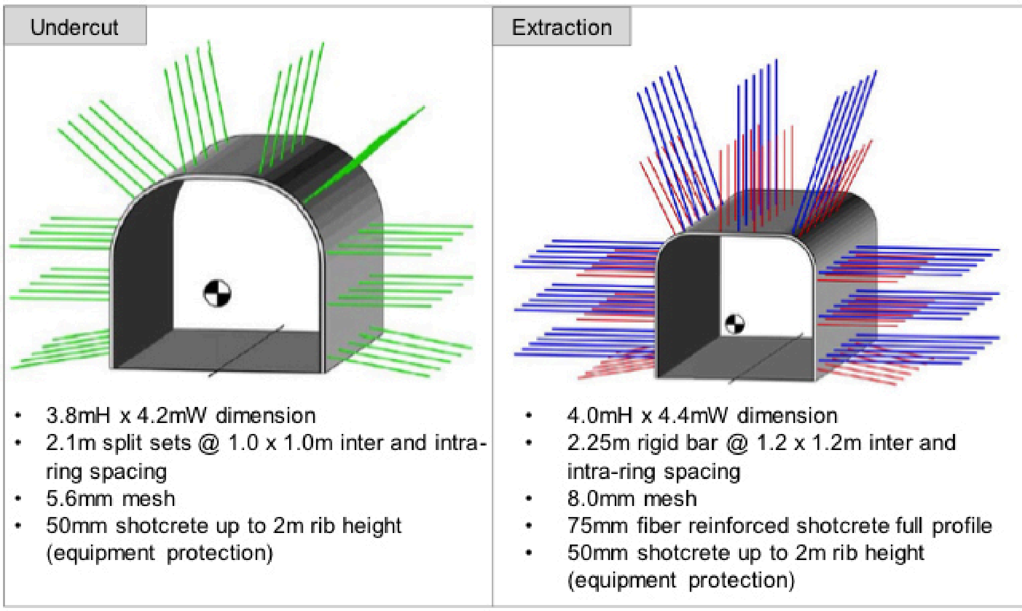

Figure 4 Pre-production design standard for exaction and undercut level ground support for Fair to Good rock mass and stress conditions (mH = metres high, mW = metres wide)

Table 1 PSM approach for the GBC extraction level (MDX bolt by Sandvik)

Damage class	Closure	PSM type	PSM schedule
Class 4 Partial Closure	>200 mm	Rehab	Slashing and support
Class 3 Heavy	125 – 200 mm	PSM Type 3	Mesh, MDX, cables
Class 2 Moderate	75 mm – 125 mm	PSM Type 2	Mesh and MDX
Class 1 Slight	25 mm – 75 mm	PSM Type 1	Increased monitoring
Class 0 No Damage	<25 mm	No PSM	Standard monitoring

3.2 Sequencing and pillar performance

The concurrent mining of PB2N and PB2S has provided an excellent opportunity to evaluate and compare pillar performance over two adjacent mining fronts. A similar rock mass, combined with consistent excavation geometries has permitted a comparison of pillar performance on both the undercut and extraction levels. Despite the similarities between PB2N and PB1S, the following fundamental differences in mine sequencing are noted:

- Development Sequencing: The extraction ratio of the PB2S extraction level is higher than PB2N as drawpoint drifts (i.e. stubs) are mined prior to undercutting (in PB2S). In PB2N, mining of drawpoint drifts have been deferred until the undercut has passed overhead (see as-built extraction level development in Figure 5).

- Undercut Sequencing: Compliance to undercut sequencing CMP criteria in PB2N has not been as stringent in comparison to PB2S. Of particular note, undercut lead-lags in PB2N have generally exceeded the maximum allowable distance due to scheduling restrictions (Figure 5).

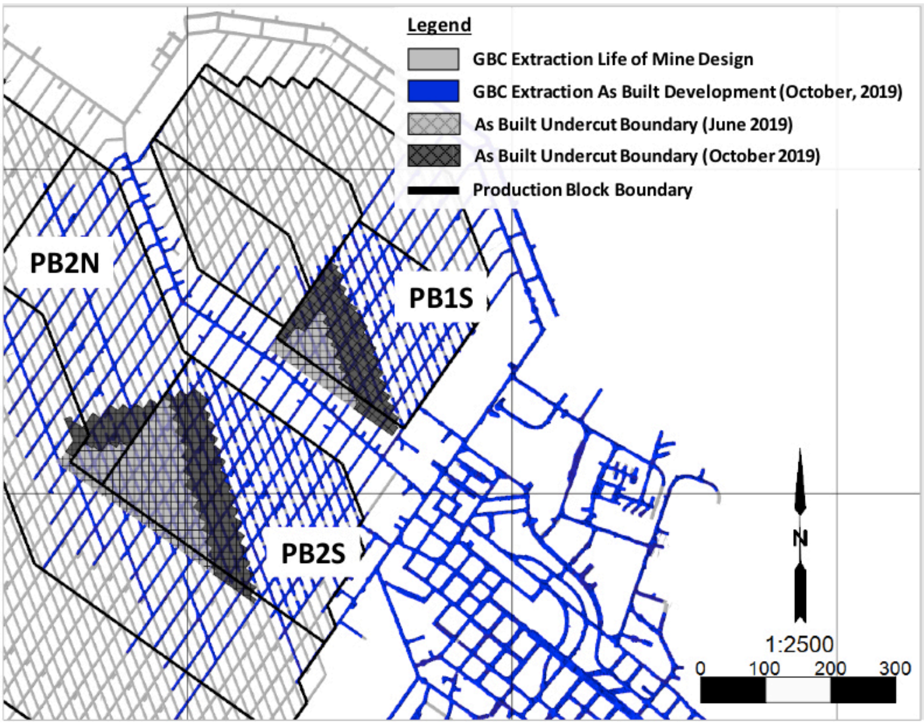

Figure 5 Extraction level development and undercut status for PB2N and PB2S (June and October 2019 undercutting geometries shown)

The Underground GeoEngineering Division at PTFI includes a well-established monitoring team. Routine excavation monitoring includes high resolution static and mobile scanning, automated extensometers and manual convergence measurements. A strong focus is placed on the measurement of excavation closure, pillar bulking and depth of damage. Data are processed daily and decisions are made on a near real-time basis. Example images and monitoring data from the PB2 undercut and extraction levels are provided in Figure 6 and Figure 7, respectively.

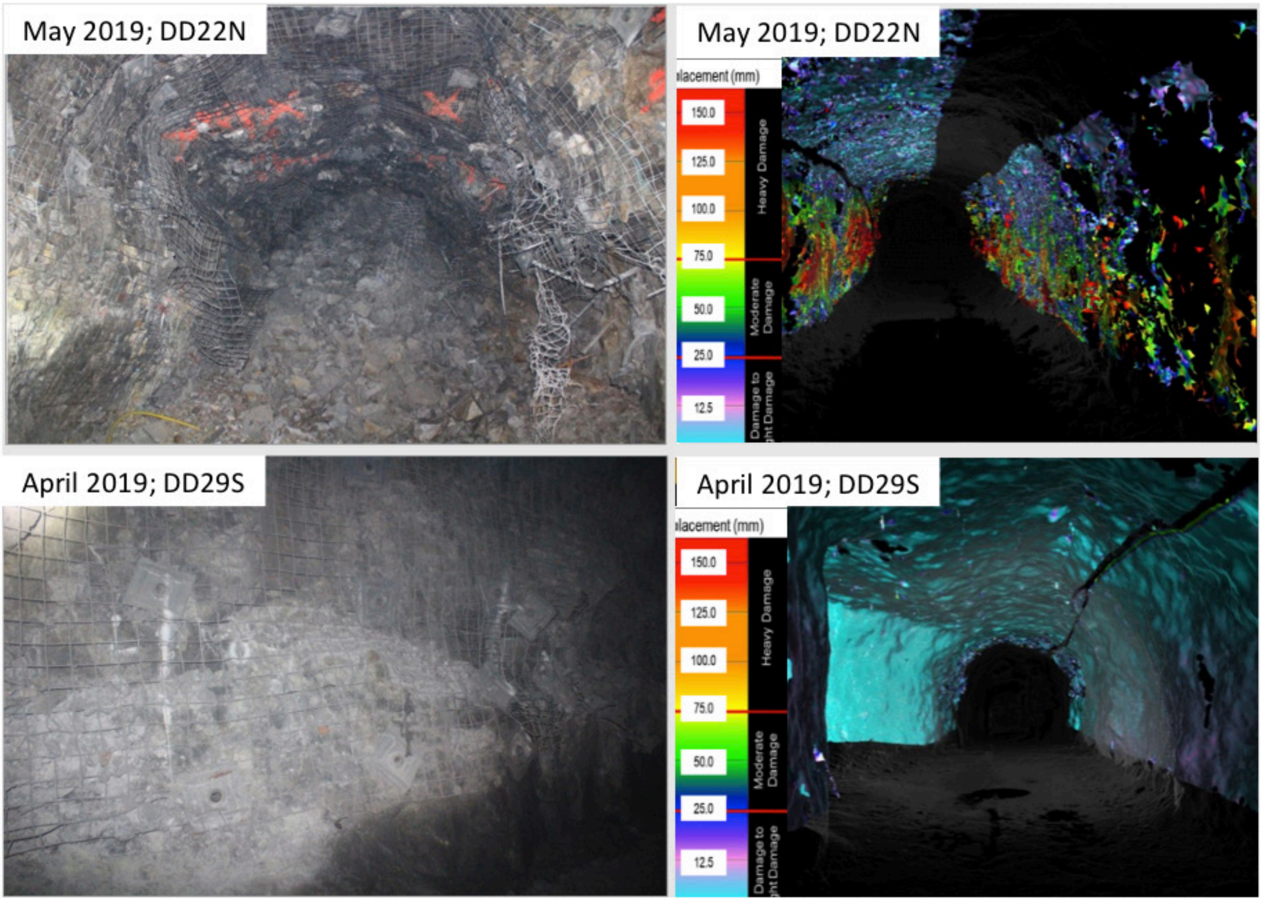

Figure 6 **Undercut level damage at PB$_2$N (DD$_{22}$N) and PB$_2$S (DD$_{29}$S). Scans, showing mm of closure, and images are from the same location over the same time period. Note the aggressive closure in DD$_{22}$N (PB$_2$N) in comparison to DD$_{29}$S (PB$_2$S)**

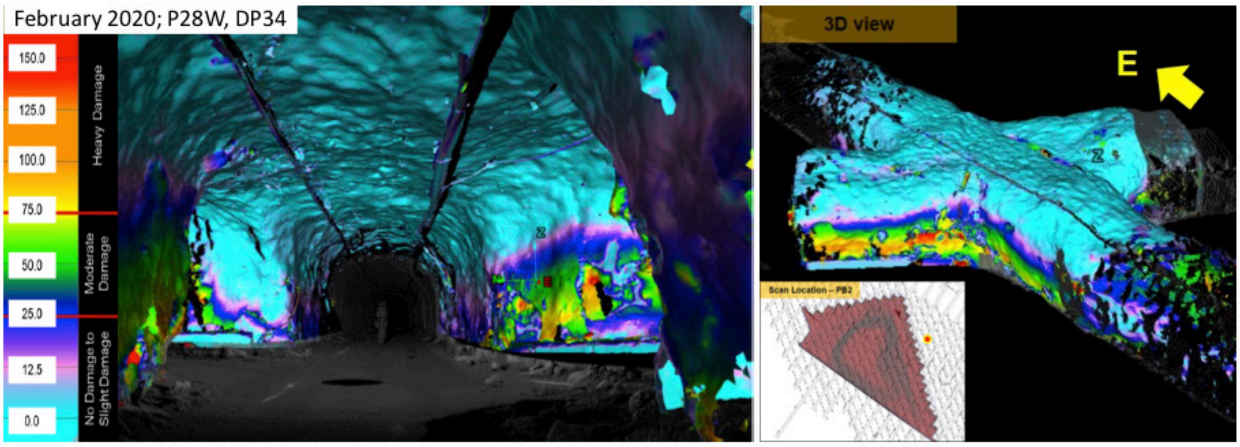

Figure 7 **Extraction level pillar damage in PB$_2$S where drawpoint turnouts were blasted ahead of undercutting (up to 75mm closure noted on ribs in PB$_2$8W over a 6 week period; note scan position relative to cave front (right inset image)**

4 Analysis and lessons learned

Numerical modelling has provided a comprehensive forecast of anticipated footprint performance. Since the initiation of undercutting, a robust monitoring dataset has been compiled allowing the geoengineering team to evaluate pillar performance in near real-time. As cave growth rapidly advances in the GBC, an excellent opportunity exists to evaluate the numerical simulations against measured footprint performance to help guide decisions on mining and ground support strategy.

4.1 Forecasted pillar performance

Several rounds of footprint scale numerical model simulations were conducted prior to the initiation of undercutting in GBC. The main modelling tool is Coupled Cave Flow, Discontinuum Finite Element analysis. In this type of model, movements inside the cave due to draw, stress and strain changes outside the cave, and the evolution of instability in the cave back are all simulated to forecast work area conditions, cave growth, subsidence and seismic event potential (Beck & Putzar 2011). These simulations aided in the optimization of undercut and development sequencing within operational constraints. Beyond the ongoing measurement-analysis-design cycle, the high quality observational data is used to confirm the geotechnical environment is responding to mining as expected, to identify and manage evolving hazards and to conform that control measures are effective. An example snapshot of forecasted strain for Q3-2019, with the current cave shapes, is shown in Figure 8.

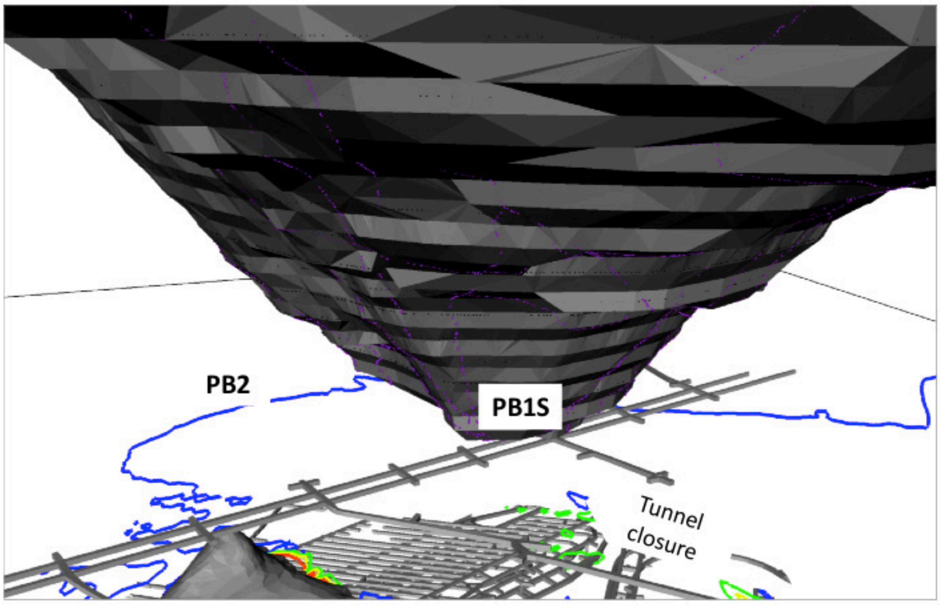

Figure 8 Modelled strain for the GBC undercut for Q3-2019

The key lessons from the measurement-analysis-design cycle so far, were:

- The value of high resolution structural geology information available early in the mine life. The resolution of the structural model is a limit on the potential resolution of the model, so improved structural data permits more reliable forecasting.
- The importance of simulating the extraction sequence in fine steps (e.g. quarterly or better) to replicate the stress path in the work areas, infrastructure and the cave back. This is especially important when confirming the decisions on the timing of footprint excavations relative to undercutting, to ensure the stress path is sufficiently captured and for forecasting seismic event potential and ground support demand.

- The value in close cooperation between geology, planning and rock mechanics teams as the mining strategy is developed, control measures are designed and the plan is adjusted to suit the as-found conditions.

4.2 Data analysis

Since the early stages of PB2 undercutting, both the undercut and extraction level pillars have responded to abutment loads. Shallow bulking of pillar ribs has been the predominant mode of deformation.

Undercut pillar response to abutment loading varies between PB2N and PB2S (see example in Figure 6). Figure 9 illustrates cumulative closure measured to data ahead of the undercut fronts through the end of Q2-2019. The relationship between lead-lags and undercut drill drive closure can be seen with higher closure rates in PB2N where lead lags exceed recommended dimensions.

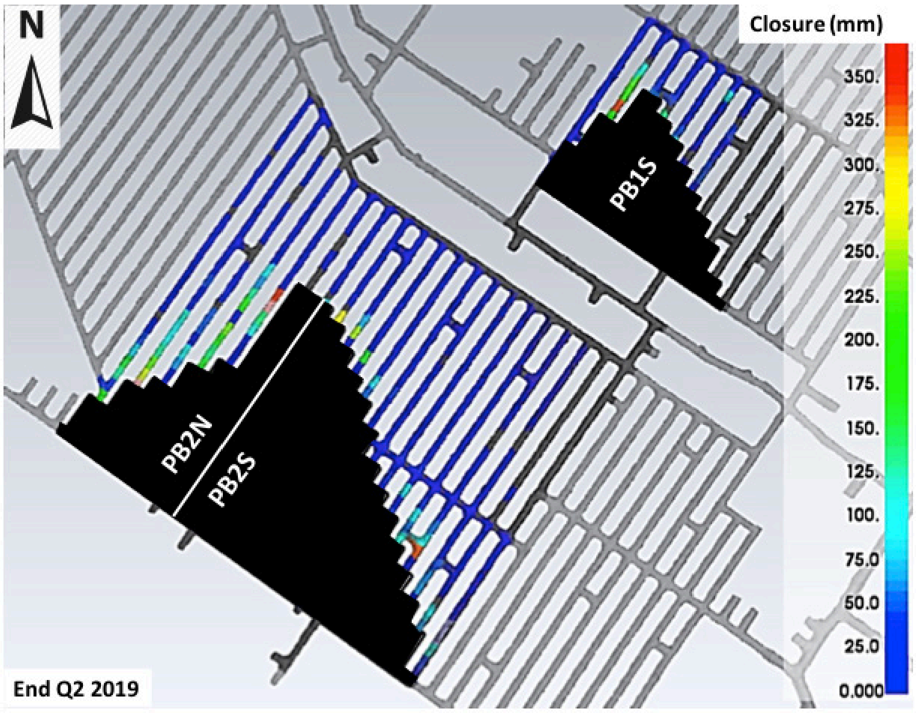

Figure 9 Cumulative convergence on the GBC undercut through Q_2-2019 (closure measured from rib to rib; drill drives spaced 15m along drive centrelines)

Single wall convergence, plotted against distance to undercut front, is shown in Figure 10. An increasing trend of damage is evident when measured closer to the cave abutment. This measure is important as the observed convergence is primarily due to dilation of yielded material (which results in ground support capacity loss).

Analysis of convergence and depth of damage data allows for calibration of empirical relationships used in ground support design. Specifically, assumed spalling initiation threshold and bulking factor can be modified based on observed ground performance and used to drive ground support selection. This calibration, which helps direct PSM scheduling, has already been successfully implemented in at the adjacent DMLZ cave mine.

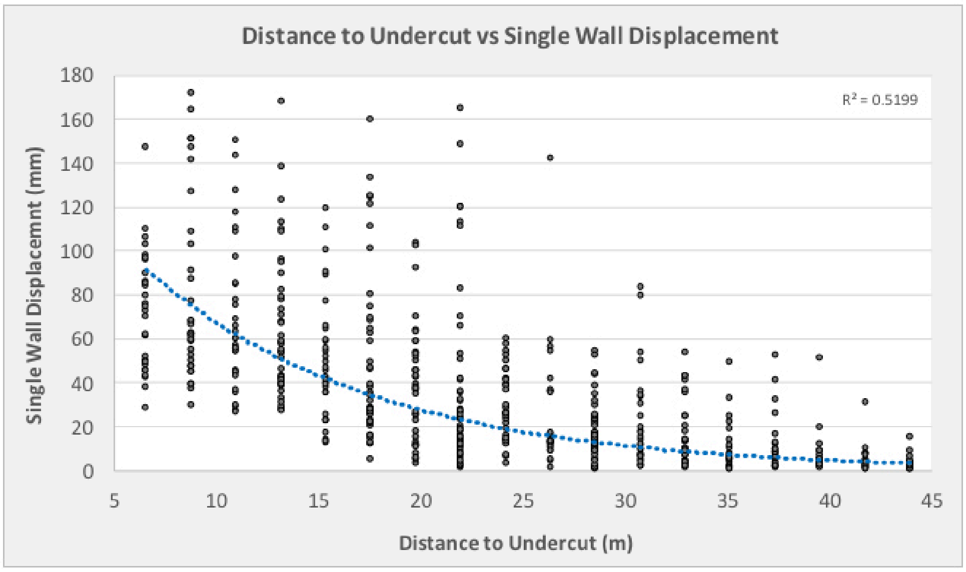

Figure 10 Single wall displacement in undercut rib pillars against cave front distance

4.3 Relevance of managing criteria for the GBC

Table 2 provides a commentary on early learnings relating to select CMP, GCMP and mine design criteria. Although observations suggest that some managing criteria may be more crucial than others, it must be noted that both the PB2 and PB1S caves are relatively immature. Observations made at this stage of mining are likely to evolve as the caves mature.

Table 2 Prominent design and production criteria with comments on PB2N and PB2S experiences to date (compliance importance ranked from a ground response perspective)

Managing criteria	Perceived compliance importance	PB2N comment	PB2S comment
Lead lag	Undercut – High Extraction – Low	Exceeded lags; local drive closure	Lags in compliance; minor damage only
Undercut front length	Undercut – Low Extraction – Low	Front length within compliance	Front length slightly exceeding compliance
Undercut advance rate	Undercut – Moderate Extraction – Low	Advance rate below minimum criteria	Advance rate within recommended range
Cave back geometry	Undercut – High Extraction - Moderate	Cave back geometry not compliant	Cave back geometry compliant
Deferred stubbing	Extraction – High	Stubs deferred until undercut has past	Turnouts developed ahead of undercutting
Bulking and spalling criteria	Low to Moderate	Limited data available at time of writing	Bulking and spalling criteria under review
Ground support standards	Moderate	Standards not sufficient but conditions improving	Standards are sufficient

4.3.1 Lead-lags (CMP)

The lead-lag target is 13 m with minimum and maximum criteria set at 5 and 18 m, respectively. Information gathered to date suggests that lead-lags play a prominent role in undercut rib pillar performance. In

PB2N, where lead-lags periodically exceeded the maximum permissible length by over 200%, rib pillar bulking was most pronounced (Figure 6 and Figure 9). Alternatively, PB2S undercut rib pillars experienced limited damage with favourable lead-lags. Based on results to date, lead-lag compliance is considered highly important to undercut pillar stability.

4.3.2 Undercut front length (CMP)

Undercut front length, set at a maximum length of 250 m, is measured at right angles to the drill drives to remain independent of lead lag criteria. The "Equivalent Undercut Length" (EUL) is defined as the undercut length measured diagonally along the cave front from drill drive centreline to drill drive centreline (330 m maximum EUL length based on 13 m lead-lag). At the time of writing, the measured EUL range for PB2N is within the maximum recommended length while PB2S slightly exceeds the recommended length. The lack of widespread instability along the PB2S front suggests that this criteria is not a critical control on footprint stability.

4.3.3 Undercut advance rate (CMP)

Undercut advance rate can have an impact on pillar performance, particularly undercut pillars, if rates are too low allowing for accumulation of strain. If rates are too high, drawbell opening cannot keep pace and adverse cave shapes can develop. The minimum and maximum rates are currently set at 5 rings/month (11 m) and 8 rings/month (18 m), respectively. Current advance rates, averaged over the last five months, are 7 m/month for PB2N and 11 m/month for PB2S. Although bell opening has kept pace with these rates, low advance rates, particularly in PB2N are believed to have had at least locally negative impacts on undercut pillar performance (especially where combined with out-of-compliance lead-lags).

4.3.4 Cave back geometry (CMP)

The managed segments of cave back geometry include the veranda and the draw angle zone (Figure 11). The veranda, defined as the area of the cave where draw is immature and characterized by flatter cave back angles, is measured along the panel drive from the last open drawbell to the undercut front. Veranda length and cave back angle are ultimately controlled by drawbell opening rate and mucking (i.e. cave shaping).

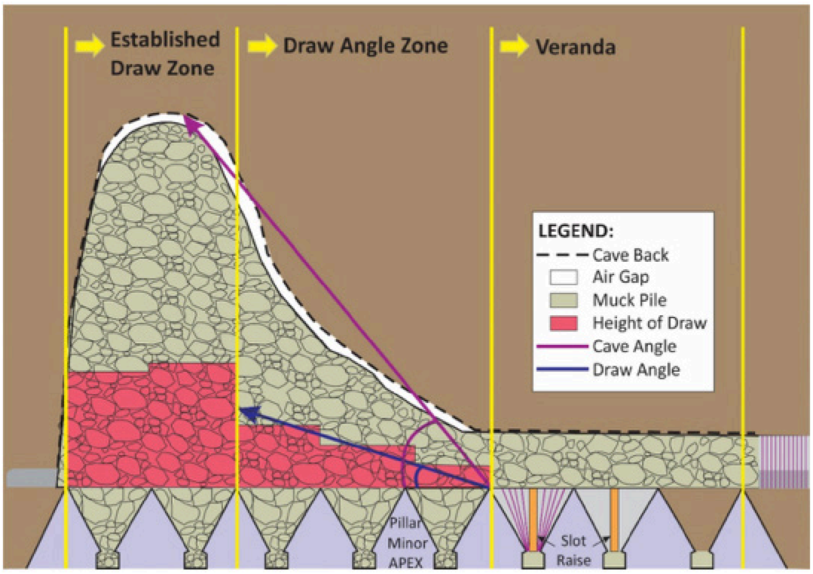

Figure 11 Managing cave back geometry criteria per the GBC CMP

The current criteria state that the veranda must not exceed a length of 50 m. The draw angle recommendation, driven through HOD, is used to manage the physical cave back angle. Where the 35° minimum cave angle is not achieved, bells will be moved into the veranda inventory. Drawbells may be fired once a 45° angle is achieved between the bell and the undercut front (nominally 18-20 m depending on sill thickness; Figure 11).

The cave back angle and veranda arrangement are known to be a controlling factor on footprint pillar stability in the DMLZ mine. Specifically, where veranda geometry exceeds 50 m and cave back angles shallow below the minimum guideline of 35°, pillar damage is noted to increase (adverse abutment loading conditions are deemed to be the cause of this damage as derived from empirical learnings and numerical modelling back analyses). Much like the DMLZ, cave back angle correlates well with pillar performance in the GBC. This correlation is especially evident on the undercut where highest degrees of damage were observed ahead of the PB2N cave front (where the cave angle sits below the minimum 35° criteria).

4.3.5 Deferred stubbing (mine design)

More is being learned about the advantages related to deferred stubbing on the GBC extraction level. As the schedule impact is significant, the benefits to pillar stability must be clearly demonstrated to management for sequencing decisions in future production blocks.

A focused monitoring program on the extraction level is aimed at evaluating the benefit to pillar performance from deferred stubbing. Preliminary results suggest that pillars do respond more favourably when stubs are fired following undercutting (overhead). Additional data will be gained through more advanced stages of undercutting as well as cave loading in the coming months and years so that the perceived advantage (from a pillar performance perspective) of deferred stubbing can be better quantified. This expanded dataset will drive extraction level development sequencing in future production blocks.

4.3.6 Bulking and spalling criteria (GCMP)

Initial depth of failure and convergence measurements indicate that there is a potential underestimation of bulking factor (5% as per GBC standard design) assumed in the ground support design. Although the relatively limited dataset makes modification of the existing bulking and spalling criteria challenging, early indications suggest that development of a GBC-specific ground behaviour model will allow for refinement of these key parameters.

4.3.7 Ground support standards (GCMP)

Ground support deployed for undercut excavations in PB2S consisted of split sets and mesh in standard ground conditions. Based on pillar bulking and locally aggressive rates of ground support consumption, the philosophy of ground support for PB2N evolved to include rigid and rigid/end anchored bolts. While this change is not predicted to eliminate the need for PSM in the undercut level, rates of support maintenance have been reduced.

A recent review of undercut level displacement and depth of failure data suggest that ground bulking is typically limited to 1.0 m depth (into ribs and backs). These data will continue to be analysed against PSM recommendations (e.g. to assess the remnant capacity of split sets against the need for additional bolting).

Ground support, as a contributing factor in footprint stability, is considered to be of moderate importance relative to other managing criteria. Regardless, the value of timely PSM is critical to overall excavation stability, safety and production continuity. Undercut front advance rates, lead-lags and cave back geometry are considered critical controls on ground support performance.

5 Conclusions

In general, both undercut and extraction level pillars within the GBC footprint have performed well to date. Compliance to stated ground control practice, caving rules and scheduled draw call has been strong. Where criteria have not been met, locally aggressive pillar damage has occasionally been observed. Lead-lags and cave back angle, especially the veranda region, are considered to be the most critical managing criteria.

Learnings to date are being used to adjust GCMP, CMP and mine design criteria so that safety and production can be optimized. PTFI planners will reduce reliance on standard best practice guidelines to apply more customized criteria best suited to the GBC operation. As the footprint pillar monitoring database expands, further insight can be gained on the flexibility of managing criteria.

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