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Grasberg block cave production schedule calibration

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ABSTRACT

The Grasberg Block Cave mine (GBC) has been in production since 2018 and is a significant production contributor to Freeport Indonesia. GBC produced better head grades than vertical mixing cave models indicate when simulating historical depletion. The production differences between actual and modeled initiated the effort to develop a calibrated production scheduling model. With the observed differences, the uncalibrated model does not reflect the flow mechanisms active in GBC. Understanding the physical mechanisms governing cave growth and mixing is critical to balancing modeled depletion versus historical metal production. Available data including seismic interpretations, beacon data, cave-to-surface expression, and grade data was collected and analyzed to assist in forming an understanding of the caving mechanics. The study of the historical data suggests that the macro cave growth dynamics have played the most significant role in grade model accuracy at GBC compared with locally varying flow mechanisms. Even minor amounts of variable caving rates or non-vertical cave growth may have a notable impact on the timing of material at the extraction level. The GBC calibration study resulted in a model that accurately predicts the historical depletion of the orebody. This paper summarizes the methods and techniques used to produce a calibrated model for use in production forecasting.

1 INTRODUCTION

1.1 Background

Estimated copper production from Grasberg Block Cave (GBC) exceeded forecast grades throughout 2022 and 2023. The Production Planning Team was tasked with updating the PCBC model to ensure mined metal was correctly depleted from the PCBC model (and therefore depleted correctly from block model resources). Secondly, improving the historical metal balance between mine and model using the correct mechanisms would theoretically improve near-term grade predictions. To that end, the team set out to accomplish this in three main steps:

1. Establish metal balances through mill production.
2. Understand the potential flow dynamics and cave growth history.
3. Capture the most likely caving hypothesis into PCBC.

1.2 Metal Balances

Calibrating the production schedule model requires a clear understanding of the actual mine grade. The mine conducts drawpoint sampling, and while these assays provide valuable data they tend to bias towards the finer fragments in a muck pile.

Although drawpoint sampling is available and can provide trend data, the data does not align with actual metal produced. At the PT Freeport Indonesia (PTFI) Grasberg District mining complex, multiple sources feed the mill circuits. The GBC mine grade was back calculated from the mill head grade to develop a proper calibration target. Figure 1 below shows the difference between the mine sample assays and the back calculated GBC mine head grade.

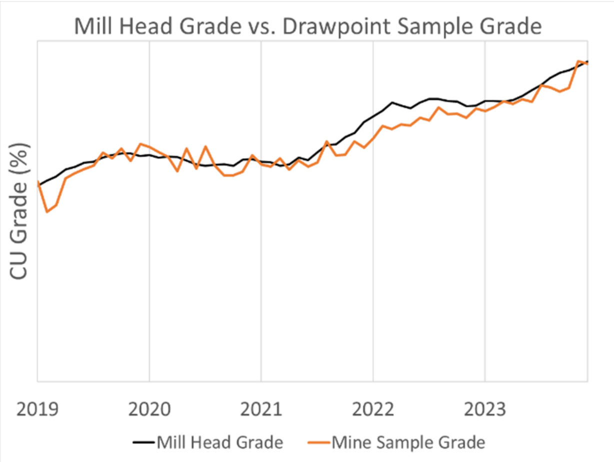

Figure 1 Mine vs Mill Grade.

2 CAVING DYNAMICS AT GBC

2.1 Overview

Long-term and production block scale metal depletion and forecast accuracy for a large cave footprint like GBC appeared to be heavily dependent on cave growth rates and dynamics. Locally variable conditions such as interactive vs isolated draw and fines movement also play a role in forecast accuracy. However, for a mine of this scale, local variability in draw width could not account for most of the grade variability in the absence of cave shape control and the timed release of material in PCBC Marker Mixing (MMIX).

2.2 GBC Caving Hypothesis

The PT Freeport Indonesia (PTFI) geotechnical and geology teams collect vast amounts of data and have put together a series of cave interpretations. The Production Planning Team incorporated this work and studied the available spatial/geotechnical data coupled with historical draw and grade over time to create a working hypothesis for incorporation into PCBC.

The hypothesis is that the cave experienced spatially variable cave propagation shortly after GBC began drawing from the extraction level. The cave appears to have grown preferentially to the north by northeast towards the stockwork near the bottom of the Grasberg open pit. This is supported by several data sources, including: seismicity and associated interpretations, Elexon beacon and smart marker data, the location and timing of the cave breakthrough into the Amole level, and the location and timing of the surface breakthrough. The height of draw (HOD) (Equation **1**) is relatively low when the amole and surface breakthroughs occur, and, most notably the HOD is lower directly beneath the breakthrough region.

Equation 1 shown below.

$$HOD = \frac{\sum Drawpoint\ Tonnes}{\left(\frac{Density \text{ x } Bell\ Area}{2}\right)} \quad (1)$$

Figure 2 through Figure 4 are vertical sections through PB2S looking NW and are shown below:

- Solid black lines are estimated cave growth progression based on seismicity. The shapes effectively capture the area which was seismically active but is now believed to be yielded.
- Thick dots with faint trails are Elexon beacons and their movement history.
- Red outline encapsulates part of GBC's stockwork.
- Green lines are where mapped faults intersect the vertical section.
- The dark brown line is the final open pit surface.

Early in GBC's life with a relatively low HOD the cave grows quickly and preferentially towards the Amole level to the north. The seismicity and Amole breakthrough (March 2020) location appear to follow a fault (Figure 2).

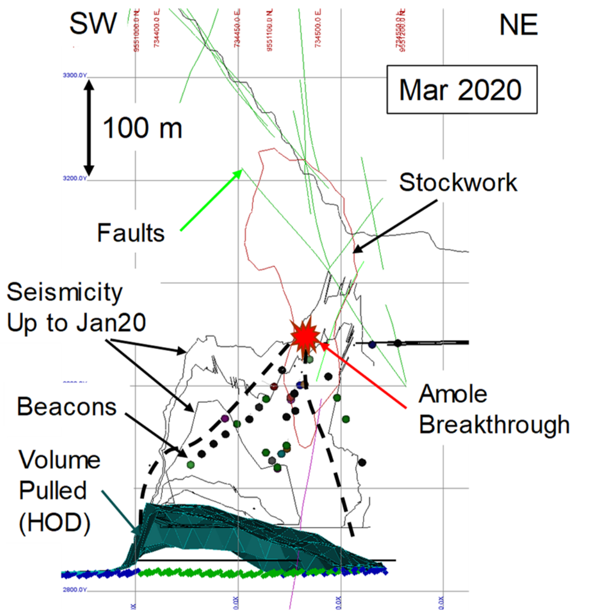

Figure 2 Vertical section through PB2S illustrating Amole breakthrough.

A few months later, the cave breaks to surface almost immediately above the Amole breakthrough. Seismicity interpretations suggests that the cave grew more slowly to the south where the HOD was highest. This is illustrated by the small distances between the seismicity shape contours (Figure 3). Elexon beacons in the vicinity of the Amole breakthrough begin moving more proportionately to the mining rate.

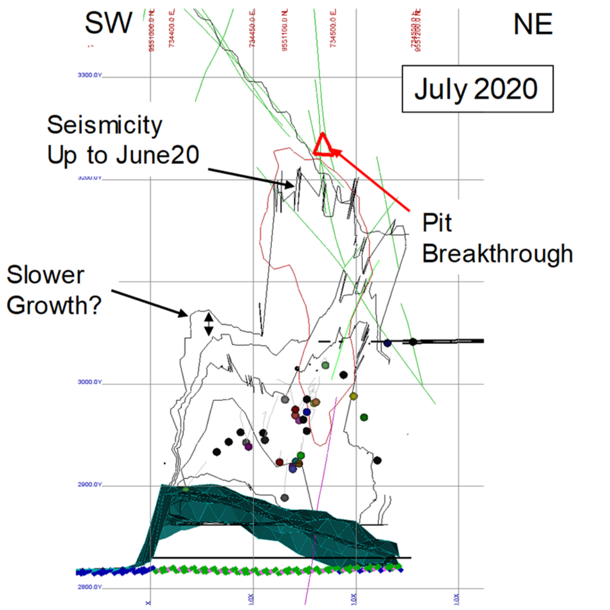

Figure 3 Vertical section through PB2S illustrating initial surface breakthrough.

The cave's surface expression then grew steadily outward from the initial breakthrough location (Figure 4).

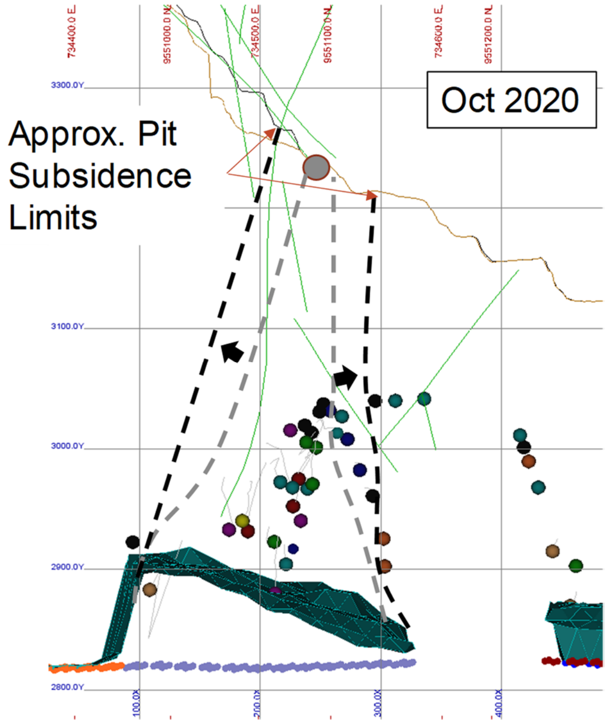

Figure 4 Vertical section through PB2S illustrating cave-surface expression changes shortly after initial surface breakthrough.

The approximate pit subsidence limits shown in Figure 4 are based on the subsidence limits from LiDAR scans of the GBC open pit shown in Figure .

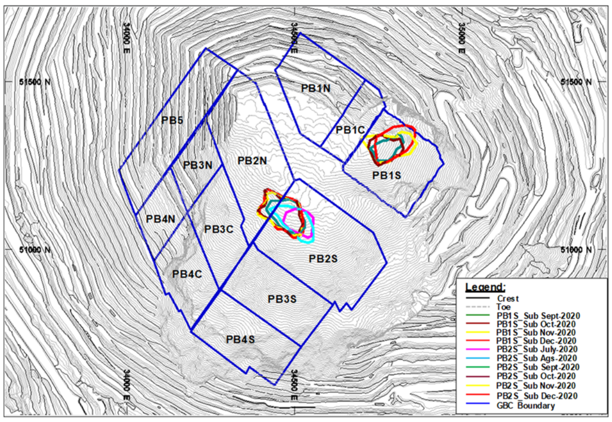

Figure 5 Estimated early cave surface expression outlines over time.

The PB2 cave surface expression then grows southeast (Figure 6) relatively proportionate to undercutting and HODs. This suggests that the cave is breaking back closer to vertical when contrasting against the initial breakthrough location and HOD profile.

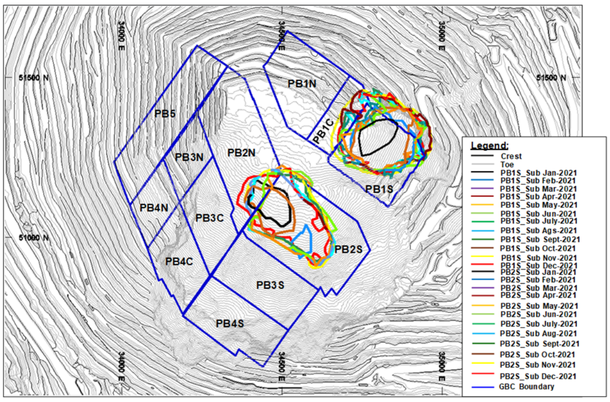

Figure 6 Estimated cave surface expression outlines over time.

The significance of the initial non-vertical cave growth is that it allowed for the stockwork to reach the footprint faster than a simple vertical mixing assumption would suggest.

3 PCBC FLOW MODELLING

3.1 PCBC Modelling Overview

Freeport uses Geovia PCBC™ with Marker Mixing flow model (Khodayari, 2022) for forecasting and reserve reporting. Marker Mixing is a direct successor to Template Mixing (Diering, 2007). PCBC calibration refers to adjusting the mixing and flow settings to better mimic actual flow and grade performance in the mine.

There are a variety of settings and techniques available to influence material flow and recovery in PCBC MMIX. The settings can, broadly speaking, be divided into two major categories: material availability, and material flow. Material availability refers to the material which is allowed to flow or not, temporarily or permanently. Material flow refers to the behavior of material which is free to flow, or in the muckpile. Material availability settings are the more likely candidate to capture the caving hypothesis mentioned above and were the primary focus of the calibration project. Material availability settings include:

- LOADCAVE: the user specifies specific material allowed to flow in a given period.
- LOADRATIO: Akin to LOADCAVE, but the material is allowed to flow as a function of HOD from the previous model step multiplied by the user specified Cave:HOD Ratio on a per drawpoint basis.
- BASE_FROZEN, HEIGHT_FROZEN, and EROSION: Refers to material availability immediately above a drawpoint. This is akin to draw width (Figure 7). This setting has some overlap with draw cone geometry definition. EROSION is the rate at which material may leave the frozen state and be recovered.

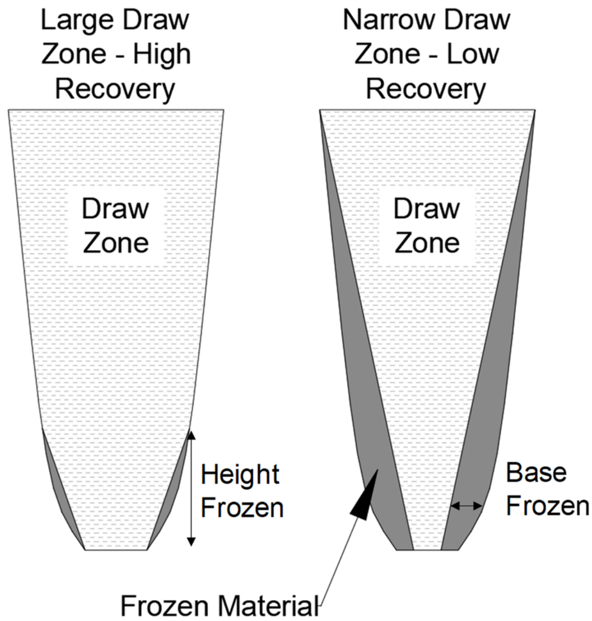

Figure 7 Illustration of HEIGHT_FROZEN and BASE_FROZEN.

The critical component for this calibration work was establishing a set of HOD to cave growth ratios for use with MMIX LOADRATIO. Cave back surfaces for use with LOADCAVE were initially considered but were set aside in favor of using ratios for a variety of reasons outlined in following sections. BASE_FROZEN and HEIGHT_FROZEN were tested and adjusted but could only account for a minority of the metal depletion differences in the absence of LOADCAVE or LOADRATIO.

3.2 Cave Flow Modelling in PCBC Using Cave Shapes

Using cave back surfaces to restrict the flow of material across time in PCBC is a commonly used technique. It is worth noting that the use of a cave shape created for geotechnical purposes (such as stress and stability modelling) does not always yield great PCBC calibration results when input directly into the Production Scheduler. Yielded or shifted rock may no longer be stress bearing or seismically active, but this does not mean that the mass is free to flow at or near the velocity of the average material in the muckpile. In PCBC, once material becomes mobile using a cave shape (LOADCAVE) it will mix and flow with the same potential velocity as other material already freely flowing (with the caveat of fines movement factors coupled with a variable fines model, i.e., FINES_LABEL). Therefore, the most appropriate definition for a cave back for use in PCBC should refer to the volume of rock believed to be highly mobilized, or the mobilized zone (MZ). Alternatively, time lagging or factoring down the cave heights of geotechnical cave shapes has been done with success at other operations including DOZ.

3.3 Cave Flow Modelling in PCBC using HOD:CAVE Ratios (LOADRATIO)

A viable alternative to using discretely defined cave shapes or mobilized zones is to use HOD ratios to define what material is free to flow in MMIX. Ratios can be built from first principles or derived from a cave shape by dividing the cave height by HOD, such that once that point in time is reached the resulting cave/mobilized shape is the same as the cave interpretation. Ratios have two main advantages over discrete cave shapes:

1. Automatically smoother lateral blending of material in the presence of uneven cave growth. The effect is the same as having well-proportioned monthly cave interpretations.
2. Allows for dynamic testing of future scenarios without the need to adjust cave shapes for new sequences. That is, assuming the cave to HOD ratios would not change dramatically when the tonnage schedule changes. Defining a procedure for establishing cave ratios based on permanent or temporary production block boundaries coupled with geotechnically or empirically derived factors mitigates this.

3.4 Cave and Ratio Settings Applied at GBC

A set of Cave:HOD ratios were derived for GBC using the cave surface expression, beacon data, seismicity interpretations, and the grade data. Cave:HOD ratios are the primary driver of the GBC calibration. The procedure was:

1. Draw a wireframe surface which intersects the chosen topography breakthrough outline (January 2021 in this case), honors known points of mobilized rock and is below any known points of solid rock.
2. Use the HOD heights at that time frame (January 2021) to calculate a height ratio between the HOD and the drawn surface.

   Figure 8 shown below has an example of the estimated mobilized zone shape. The ratio for each drawpoint is the height from the drawpoint to the Target MZ surface divided by the drawpoint HOD.

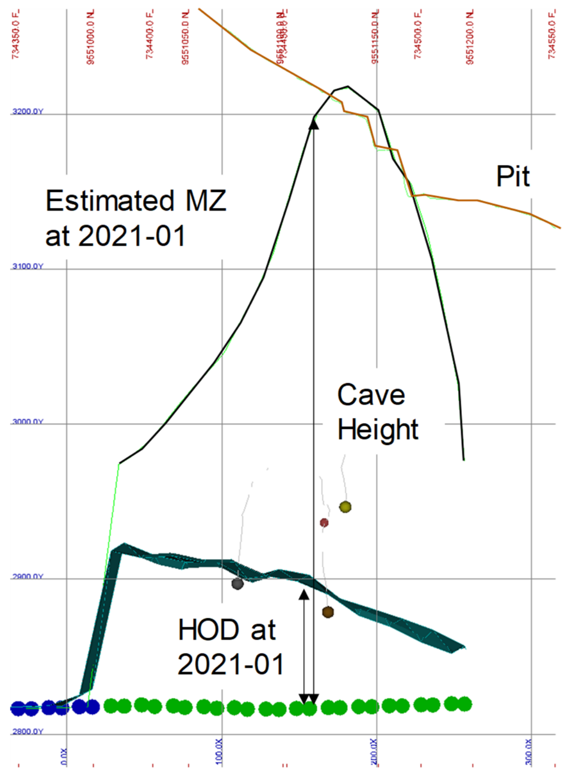

Figure 8 Vertical section through PB2S with MZ target surface and drawpoint HOD surface.

3. Evaluate the resultant flow impacts in PCBC compared to assays (spatial calibration) and global mill targets.
4. Repeat this process iteratively by adjusting the drawn surface in areas where there is no or limited measured data points until a good global and improved spatial calibration is achieved.
5. Use MMIX plot options to ensure the induced rilling seems reasonable and is moving material in a way which would explain spatial footprint grade variance (Figure 9).

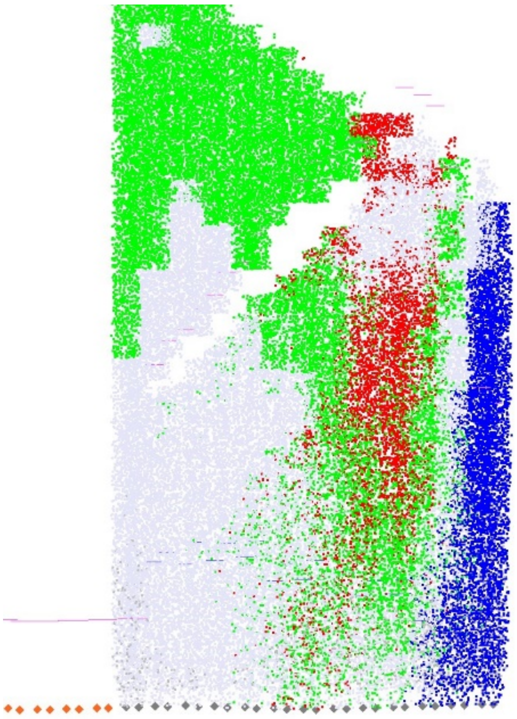

Figure 9 Vertical section through PB2S showing example MMIX markers plotted to observe particles which flow rapidly along the growing mobilized zone.

The final ratios derived from the core of PB2S are shown below in Figure . These ratios are reflective of the cave ratio zones for DMLZ, which are 0 to 2 on the veranda and cave edge, 3 to 5 in growth zone just in from the active perimeter, and >5 in cave crown (Erhardt, 2022).

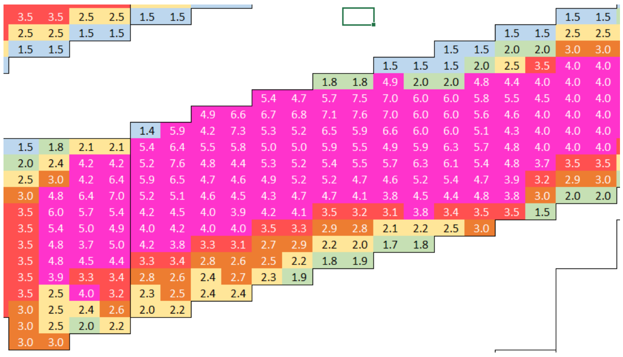

Figure 10 HOD:Cave ratios used in the GBC calibration for PB2S.

3.5 BASE_FROZEN, HEIGHT_FROZEN, and EROSION

Second to Cave:HOD ratios, the primary draw width settings, also known as HEIGHT_FROZEN, BASE_FROZEN, and EROSION were tested. A best fit experiment was tested to see if patterns of narrow draw were present at GBC. A batch of runs testing dozens of combinations of HEIGHT_FROZEN and BASE_FROZEN were run. The settings which yielded the minimum and maximum sum of absolute metal error per month per drawpoint were isolated and plotted to see if any patterns were present. The absolute percent difference between the best and worst settings were plotted to see if any clear patterns of setting sensitivity emerged, as shown in **Error! Reference source not found.**. This technique is similar in some ways to assessing area of influence (Van Hout, 2023).

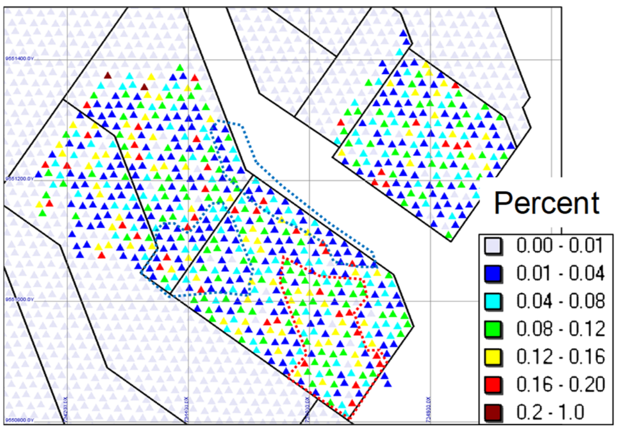

Figure 11 Plan view showing percent change between best and worst fit frozen settings.

The BASE_FROZEN, HEIGHT_FROZEN, and EROSION were ultimately set at 0.35, 200 and

0.03 respectively, globally. Using the best fit settings on a per drawpoint basis did not notably improve the global or spatial calibration and were left out for model simplicity. The use of cave ratios also mitigates the effects of the frozen settings in PCBC. As material is released continuously by LOADRATIO it becomes unfrozen more rapidly than when used with conventional vertical mixing.

3.6 GBC Pit Failure and Fines Modelling in PCBC

GBC sits immediately below the closed Grasberg Open Pit. Parts of the pit slope have destabilized and begun to fail. Some of the failed slope material has settled at the deepest part of the pit and some is gradually sliding into the mobilized zone above PB2S like a glacier.

Modelling the measured slope failures in the Grasberg Open Pit is a key component of ensuring that the PCBC model has the correct "dilution" material available at the top of the in-situ columns. Dilution is in quotation marks as much of the failed pit slope material is mineralized and above the current cut-off grade.

The GBC calibrated PCBC model uses the "External" method for adding slope failure material to columns (Diering, 2018), as opposed to the older technique of surface stacking.

The External method is key for establishing a different density and grade geometry than the pre caving in situ block model. That is, any material which undergoes a notable lateral move prior to subsiding into the cave is best modelled using the External technique. External is typically setup in two main steps:

1. Identify blocks which have undergone a notable location shift compared to their original in situ position, tabulate the material balance, remove them from the BM and set them aside as the External input into MMIX.
2. Identify where the External blocks ended up spatially before subsiding into the MZ. Assign the material from those blocks to drawpoints spatially near where the slope material begins subsiding into the MZ.

External material is introduced in MMIX as voids form at the pit topography height (Figure 12). This material is then free to flow with the remaining in situ column material.

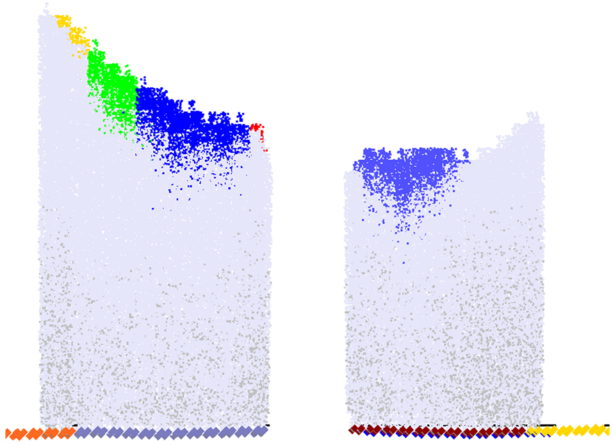

Figure 1 Vertical section through GBC showing colored External material being added to the model over time

GBC surface subsidence and slope failures are continuously monitored. The resultant shapes have been interrogated against the block model. These shapes can be visualized as per the example in Figure 13.

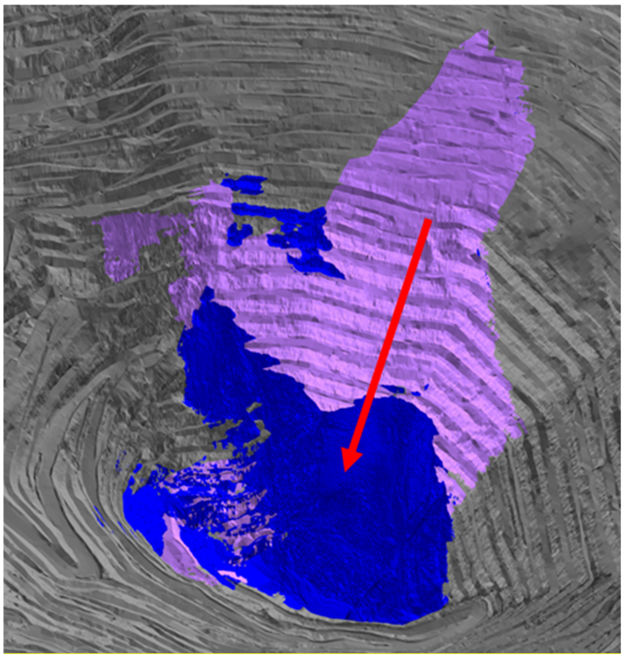

Figure 13 Example of a failure solid (magenta) filling the pit bottom (blue)

The material from these shapes is divided into three bins for addition into Marker Mixing over time. Bin one represents slope failure material which flowed into the bottom of the pit. Bin two and three represents PB1 and PB2 material which slides from up-slope and into the cave mobile zone.

4 CONCLUSION

The GBC calibration study resulted in a model that accurately predicts the historical depletion of the orebody based on data available. Some of the key findings from this project include:

- The collection and retention of information relating to early cave growth is valuable. Monitoring material flow and surface subsidence are also very useful pieces of information.
- Understanding cave growth history is a key component for understanding grade behavior at production block scale in large block caves.
- Flow and recovery around individual drawpoints yields valuable clues but seemed unable to explain overall grade trends in the absence of material availability adjustments, i.e, defining the mobilized zone over time.

PTFI will continue employing the techniques described in this paper to further improve both the accounting of metal depletion in the cave mines to date and for forward looking forecasts of future metal production.

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