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Impact of crosscut spacing on recovery and dilution at Jwaneng underground project

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Abstract

Jwaneng mine is transitioning from open pit to underground mining using a combination of blasthole open stoping, sublevel retreat, sublevel caving (SLC) and block caving methods. The orebody comprises three kimberlite pipes (North, Central and South), with the Central pipe being the focus of this study.

A 3D numerical caving model was developed to evaluate the influence of crosscut spacing on recovery and dilution within the Central pipe. Three spacings (15, 18 and 21 m) were assessed under a common draw strategy. The model incorporates key geomechanical inputs relevant to SLC performance, including fragmentation characteristics and blast ring behaviour, by constraining material flow within each blasted ring.

Model results are presented in terms of both recovery and dilution. As crosscut spacing increases, an evident decrease in global recovery is observed, consistent with decreased overlap of adjacent flow zones. Dilution and recovery trends are also evaluated and compared against published benchmarks from established SLC operations, providing context for the expected performance range for the Jwaneng underground project.

Keywords: *sublevel caving, recovery, dilution, numerical modelling, Jwaneng underground*

1 Introduction

Jwaneng mine, located in south-central Botswana about 170 kilometres southwest of the city of Gaborone, is transitioning from open pit to underground mining using a combination of blasthole open stoping (BHOS), sublevel retreat (SLR), sublevel caving (SLC) and block caving (BC) mining methods. The orebody comprises three kimberlite pipes – North, Central and South – whose spatial configuration is illustrated in Figures 1 and 2. Underground mining is planned to be implemented in two main phases across the three pipes.

This study focuses on the Central pipe, which is scheduled to be mined first. Extraction will initially be carried out using the SLR method, with a planned transition to SLC at greater depths. A transverse section through the Central pipe is presented in Figure 3, showing the base case mine design. The design consists of 13 sublevels with a spacing between sublevels of 25 m.

SLC performance is strongly influenced by drawpoint layout, sublevel spacing and crosscut spacing, which govern material flow, interaction between adjacent draw zones and, ultimately, ore recovery and dilution. Optimising these parameters is therefore critical to achieving acceptable economic and operational outcomes, particularly in large, vertically extensive kimberlite deposits such as Jwaneng.

The primary objective of this study is to assess the potential impact of crosscut spacing on recovery and dilution at Jwaneng underground mine. In addition to the 18 m base case design, 2 alternative configurations were evaluated: a reduced spacing of 15 m and an increased spacing of 21 m. These scenarios were analysed

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using a 3D numerical caving model under consistent draw control conditions, allowing for a direct comparison of their influence on modelled production performance.

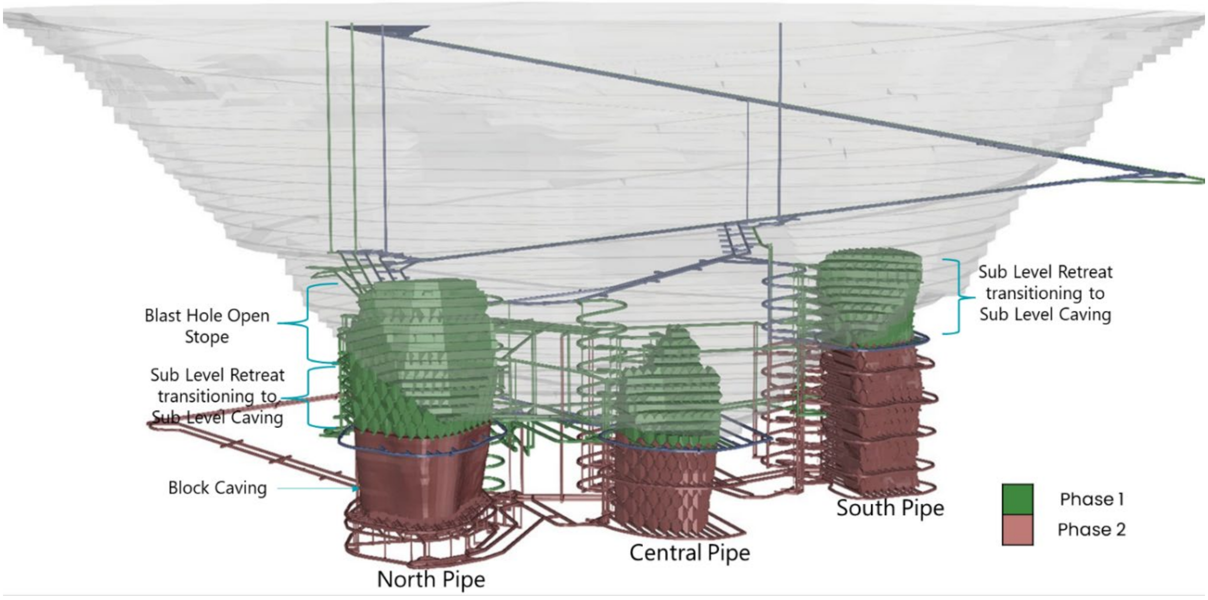

Figure 1 The orebody comprises three kimberlite pipes (North, Central and South), with the Central pipe being the focus of this study (looking east)

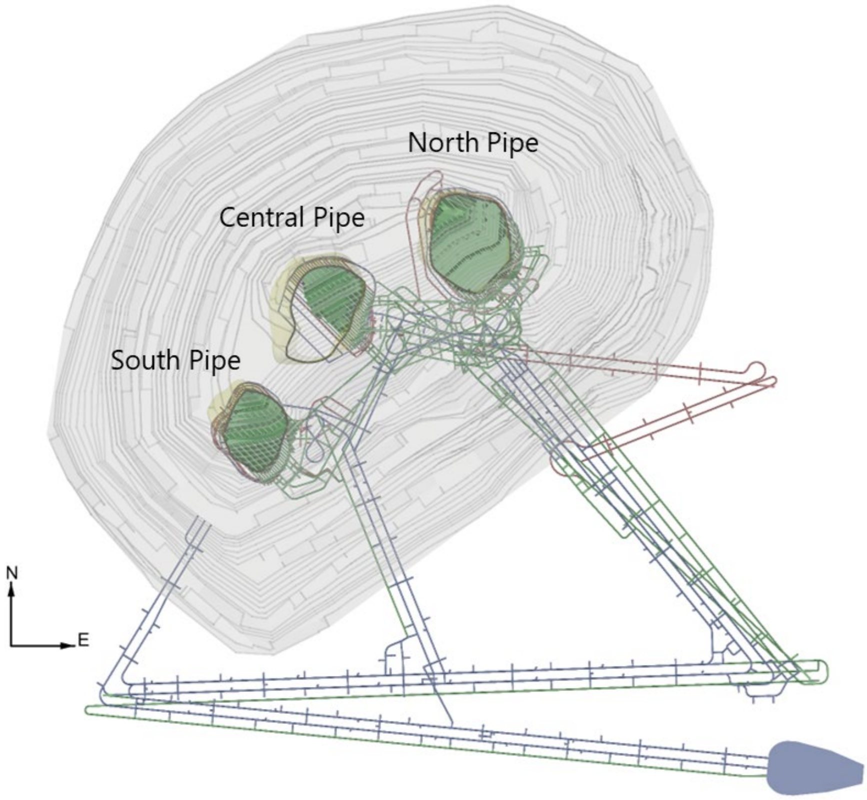

Figure 2 Plan view showing the location of the three kimberlite pipes (North, Central and South) relative to the open pit location

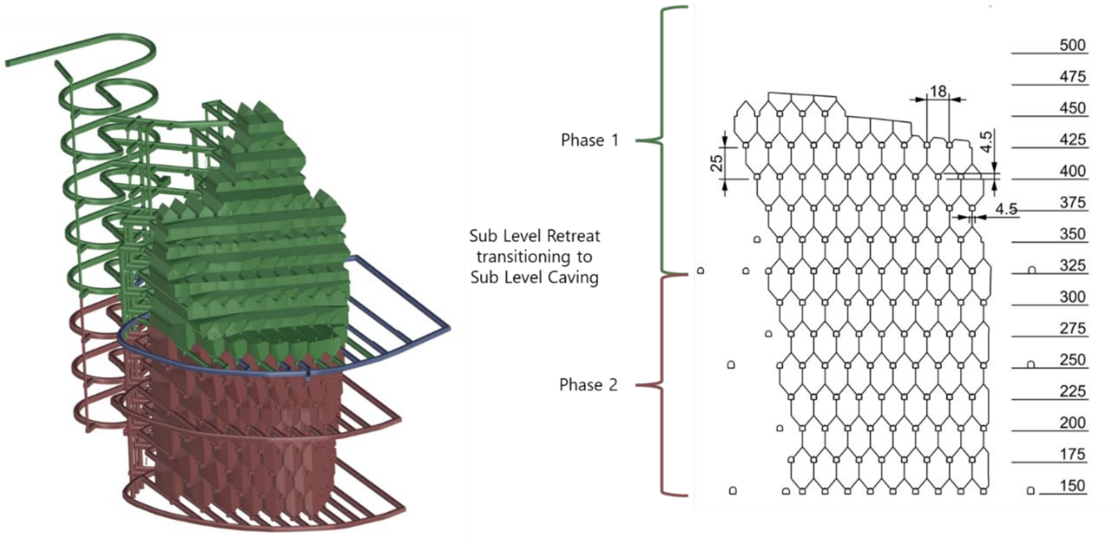

Figure 3 Three spacings (15, 18 and 21 m) were assessed under a common draw strategy for the Central pipe

2 Modelling approach

2.1 Numerical modelling framework

MassFlow software (ITASCA 2025) is used in this study to simulate material flow, recovery and dilution under SLC conditions. MassFlow follows a similar logic as its predecessor REBOP (Pierce 2010), but with a newer and sophisticated graphical interface. MassFlow is a numerical modelling tool that provides rapid analysis of the movement and extraction of fragmented rock in mining operations employing block, panel, and SLC methods.

MassFlow models flow by simulating the growth of the isolated movement zones (IMZs) above individual drawpoints as a function of production. The volume of the IMZs is directly related to the mass drawn from the drawpoint and the contrast in porosity from outside the IMZ (low porosity because it is stagnant) and inside the IMZ (high porosity because it is moving, dilating and bulking). The width of the IMZ is controlled by the fragmentation while the friction angle controls the angle at the base of the IMZ. These properties (along with grade, lithology etc.) are specified by a user-defined block model. The model superimposes a field of markers on the block model to track the movement of caved rock internal to each IMZ. The marker positions are updated on a daily basis to reflect the drawdown expected within each parent IMZ, based on the fragmentation. Markers inherit information from their parent block so that the nature and origins of material exiting each drawpoint on each day can be tracked to understand grade-tonnage trends, for example. This allows for mapping of the evolving isolated extraction zone (IEZ), which represents the original locations of drawn material.

The primary outputs of the model include time- or tonnage-based histories of extracted ore grades and material properties, spatial distributions of material above drawpoints, and 3D visualisations of IMZs and IEZs associated with each drawpoint.

2.1.1 Sublevel caving flow modelling

Material flow within a sublevel ring is generally more complex than flow above block- or panel-caving drawpoints. In SLC operations, flow is strongly bounded by adjacent intact rings and is significantly influenced by blasting performance. Ring blasting is typically conducted under choked conditions, which may result in incomplete fragmentation, compaction of previously mobilised material and back-break into neighbouring rings.

These factors lead to disturbed flow behaviour within the blasted ring. Marker trials conducted at Ridgeway mine and other SLC operations have demonstrated that the geometry of the extracted volume, defined as the IEZ, reflects the combined effects of blasting quality, confinement and material compaction.

Power (2004) identified three characteristic IEZ geometries based on approximately 60 marker trials conducted at Ridgeway mine between 2002 and 2004. These geometries are classified as:

- standard apex flow, characterised by good vertical propagation but a limited mobilisation of ring sides
- shallow flow, in which lateral mobilisation is enhanced but vertical penetration is restricted
- deviatory apex flow, resulting from poor fragmentation at the ring apex and preferential side flow.

These modes were observed to occur with similar frequency. In all cases, only a portion of the ring is recovered during the initial draw, referred to as primary recovery. Additional material is commonly recovered during extraction from underlying levels (secondary recovery), facilitated by crosscut offsets between successive sublevels. Marker trials further indicate that recovery may extend to 2 or more underlying levels, referred to as tertiary and quaternary recovery.

To model the characteristic SLC disturbed flow in MassFlow, the user defines a rectangular disturbed flow zone (DFZ) above each drawpoint within which lateral IMZ growth is restricted. Within this zone, material movement is simulated using a series of overlapping IMZs that are active over one half of the volume, approximating the ellipsoidal shape of an SLC IMZ in plan view. Once the IMZs reach the top of the disturbed zone, unrestricted growth occurs in a manner similar to BC drawpoints. Figure 4 illustrates the conceptual representation of restricted and unrestricted flow within an SLC ring as implemented in MassFlow.

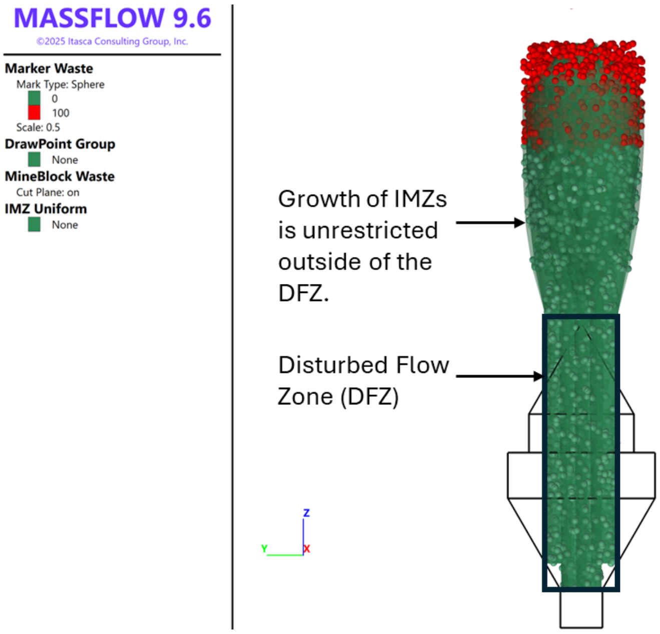

Figure 4 Representation of a restricted disturbed flow zone flow within a sublevel caving ring, as implemented in MassFlow

2.1.2 Blasting performance representation

Blasting performance is known to have a strong influence on cave flow and material compaction within SLC rings. Poor fragmentation and excessive compaction may restrict primary recovery and promote preferential flow paths.

Explicit numerical modelling of blasting processes remains challenging at mine-wide scales. Consequently, MassFlow adopts an empirical approach in which the rules governing IMZ growth are modified to reproduce the IEZ geometries observed in marker trials. This approach was developed in response to field observations, including those reported by Power (2004) and Brunton (2009). Figure 5 shows observations of marker coverage at 3 rings at Ridgeway mine's full-scale marker trials.

The advantage of this approach is that the model can be calibrated to reproduce a range of observed flow behaviours, including standard, shallow and deviatory apex flow. The principal limitation is that model performance becomes site-specific and dependent on calibration to empirical data.

In this study, blasting performance was represented through selection of DFZ dimensions (as shown in Figure 6) and fragmentation distribution to reflect expected conditions at Jwaneng (Section 2.2.3). Two conceptual blasting regimes were considered:

- good blasting performance, in which a substantial proportion of the ring material is mobilised during primary recovery
- poor blasting performance, in which incomplete fragmentation restricts initial mobilisation, resulting in lower primary recovery.

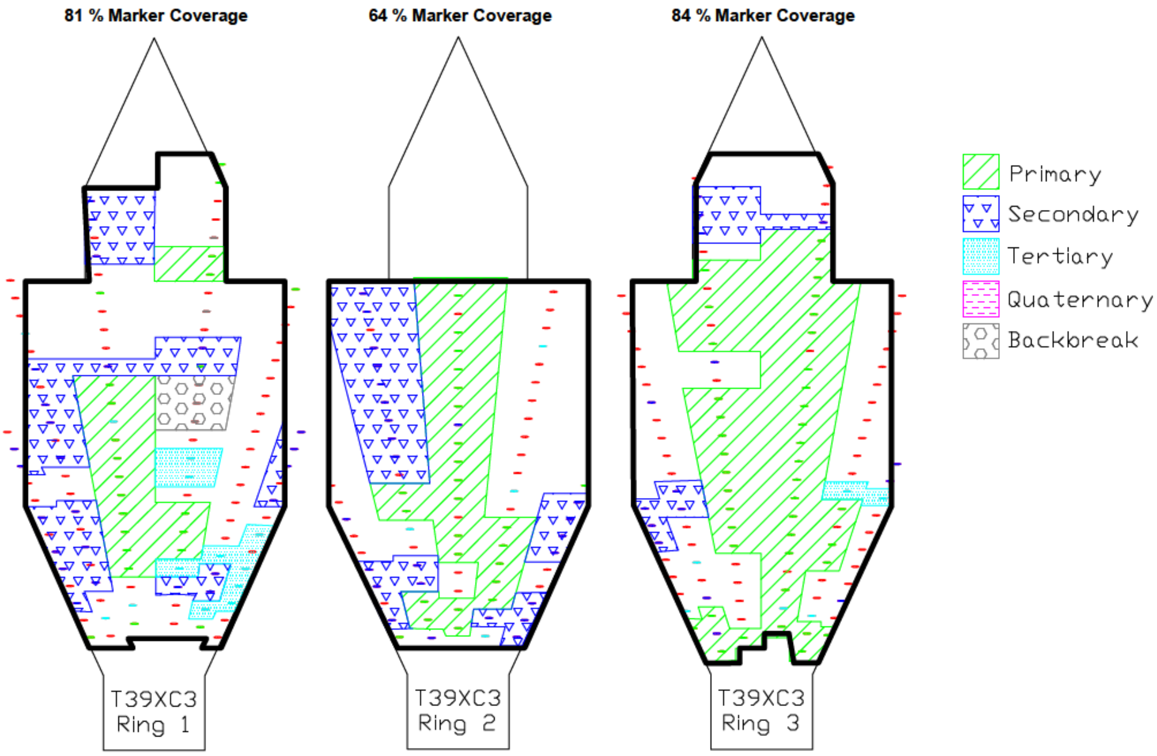

Figure 5 Ridgeway mine full-scale marker trials (Brunton 2009)

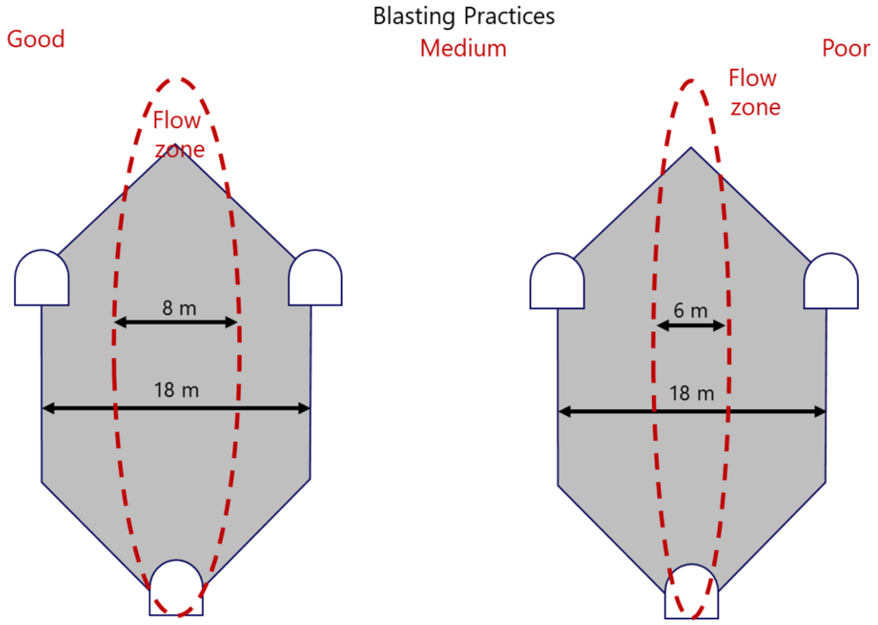

Figure 6 Schematic showing disturbed flow zone width for: good and poor blasting scenarios

2.2 Modelling parameters at the Jwaneng underground project

2.2.1 Ring design

The base case mine design comprises 13 sublevels spaced at 25 m intervals, with crosscut spacings of 15, 18 and 21 m evaluated in this study. Ring geometry, burden, spacing and hole diameters were defined in accordance with the baseline design. The overall ring design for the 3 evaluated crosscut spacing geometries is shown in Figure 7.

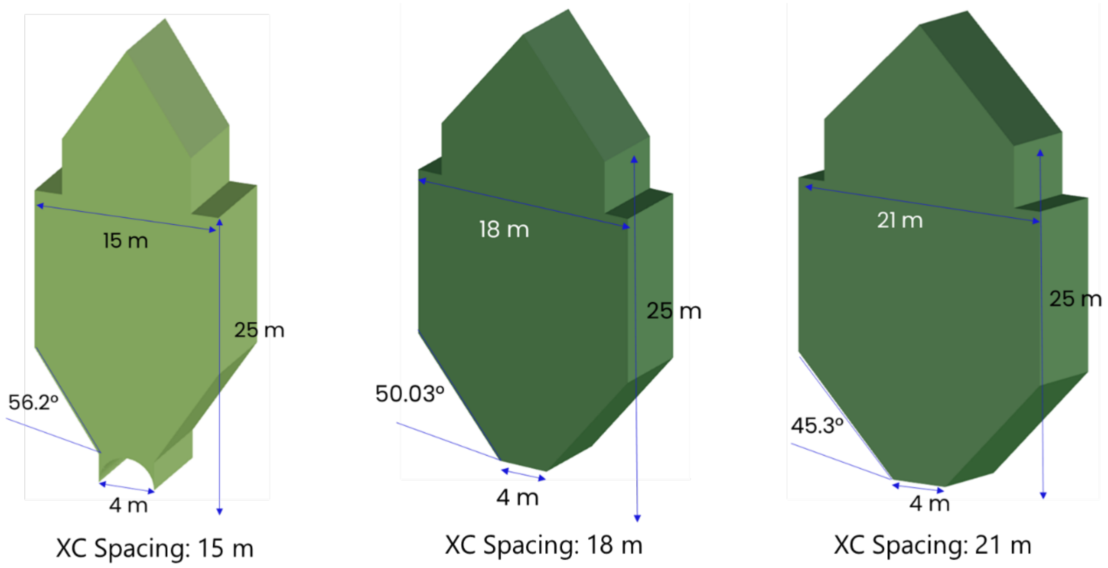

Figure 7 15, 18 and 21 m crosscut spacing ring designs

2.2.2 *Production plan and draw strategy*

A consistent production schedule and draw strategy were applied across all scenarios to isolate the effect of crosscut spacing. Shallow levels were initially under-extracted to maintain a healthy ore blanket to minimise waste dilution, followed by progressive over-extraction at greater depths to compensate overall recovery.

Table 1 summarises the life of mine production parameters for each crosscut spacing scenario, while Figure 8 illustrates the adopted draw strategy. Figure 9 shows the production plan for each crosscut spacing scenario. The differences in tonnage profiles are because these are unrefined pre-feasibility designs. Different crosscut spacings result in slightly different sequences. The position of crosscuts relative to the wedge boundaries, country rock and kimberlite contacts, and the kimberlite and breccia contacts, results in small differences in tonnes between the designs.

Table 1 Life of mine production parameters for each crosscut spacing scenario

Case	Life of mine (months)	Phase 1 extraction (Mt)	Phase 1% draw	Total extraction (Mt)	Total % draw
15 m	126 months	5.7	92%	15.8	108%
18 m	117 months	5.9	92%	16.2	108%
21 m	121 months	6.0	92%	16.3	108%

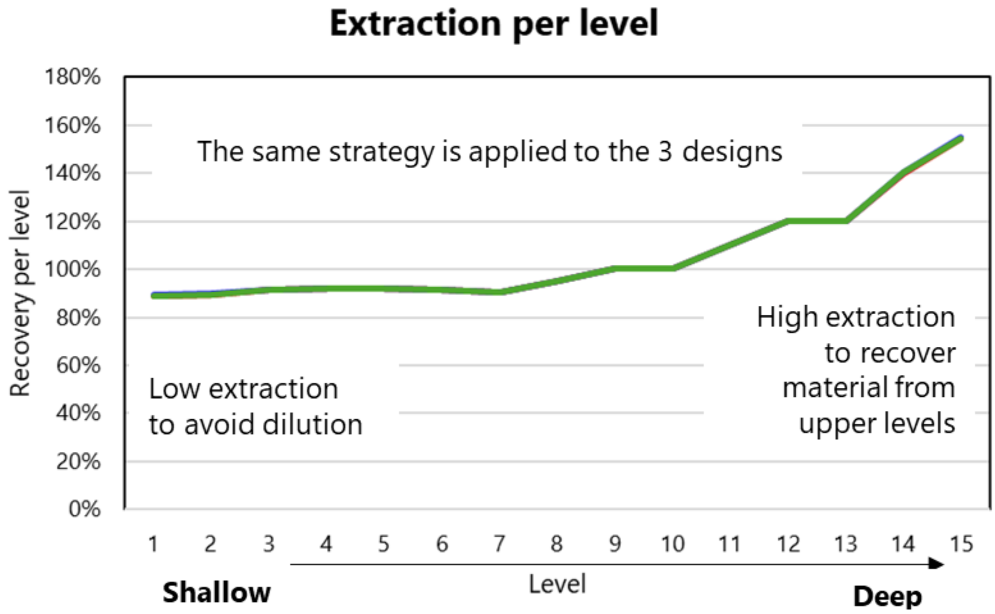

Figure 8 Draw strategy following under-extraction for shallow levels transitioning to over-extraction deeper levels

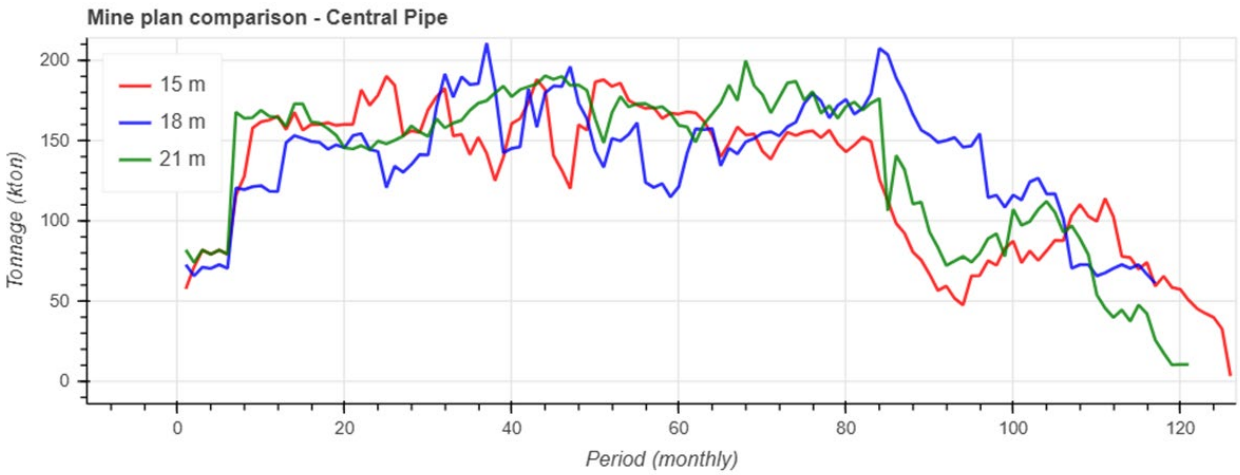

Figure 9 Production plan for 15, 18 and 21 m crosscut spacings

2.2.3 Fragmentation

Fragmentation characteristics were incorporated into the model using size distributions derived from blasting design parameters and empirical fragmentation prediction methods. For Jwaneng, fragmentation distributions were estimated using the modified Kuz–Ram methodology adapted for SLC conditions for good and poor blasting conditions.

Benchmark data from established SLC operations, including Kiruna (in Sweden) (Maripuu 1968; Wimmer 2008), Ridgeway (Power 2004), and Ernest Henry (Queensland, Australia) (Campbell 2018), were used to contextualise the Jwaneng fragmentation assumptions†. A comparative summary of SLC geometry, rock mass properties and fragmentation distribution is provided in Table 2.

† It is worth noting that this benchmark does not consider kimberlite as the primary ore type, and that weaker kimberlite typically results in a finer fragmentation distribution.

Table 2 Benchmark comparison of sublevel caving geometry, rock mass properties and fragmentation distribution

Reference	Jwaneng * –	Kiruna (Maripuu 1968)	Ridgeway (Power 2004)	Kiruna (Wimmer 2008)	Ernest Henry (Campbell 2018)
Sublevel caving geometry					
Sublevel height (m)	25	9	25	28.5	25
Crosscut spacing (m)	18	10	14	25	15
Number of blastholes	8–9	10	8	7	8
Burden (m)	2.5	1.8	2.6	3	2.2–3.0
Blast ring design					
Blasthole diameter (mm)	89	51	102	115	102
Explosive type	Emulsion	ANFO	Emulsion (1.1 g/cc)	Emulsion	Emulsion (0.9–1.25 g/cc)
Powder factor kg/t	0.47	0.15–0.17	0.5	0.23	0.32–0.47
Rock mass properties					
Rock type	Kimberlite ore	Magnetite ore type d	Volcanics	Magnetite ore type b	Felsic volcanics
UCS (MPa)	20–25	140	116	140	112
Fragmentation distribution					
P20 (mm)	40 (good) – 120 (poor)	7–90	10–300	1–70	54–113
P50 (mm)	100 (good) – 200 (poor)	38–300	70–900	15–260	204–229
P80 (mm)	210 (good) – 300 (poor)	140–600	190–1,800	105–500	356–431
Measurement technique	–	Sieved	Photographic	Sieved	Laser Scan
Comments	* Estimated values for Jwaneng SLC based on Kuz–Ram empirical methodology modified to SLC	Five blasts with 41 samples sieved for various draw tonnages	Analysis from photos undertaken for 4 blasts for various draw tonnages	One blast with 6 samples sieved for draw tonnages < 10 % of design ring tonnes	Six drill and blast trials consisting of 10 blasts per trial for various draw tonnages

2.3 Definition of global recovery and dilution

For the purposes of this study, dilution is defined as material extracted from an SLC drawpoint that originates outside the blasted ring boundaries. Dilution may include either waste or low-grade mineralised material. Recovery is defined as the proportion of in situ material within blasted rings that is successfully extracted through the drawpoints. Figure 10 shows an isometric view illustrating the proportion of material (blue colour) within the sublevel rings and the external material considered as dilution (grey colour).

Dilution and recovery are expressed as percentages and calculated as follows:

$$Dilution\ (\%) = \frac{T_{RecNonBlast}}{T_{Blast}} * 100$$

$$Recovery\ (\%) = \frac{T_{RecBlast}}{T_{Blast}} * 100 \tag{1}$$

where:

$T_{RecNonBlast}$ = extracted material originating outside blasted rings,

$T_{RecBlast}$ = extracted material originating within blasted rings,

T_{Blast} = total blasted material within the evaluated rings.

These metrics were computed consistently across all modelling scenarios to enable direct comparison of the effects of crosscut spacing on production performance. Evaluation of primary, secondary, tertiary etc. recoveries was not considered for comparison between each scenario. However, it is expected that primary and secondary recovery will decrease as crosscut spacing increases (Dunstan & Power 2011).

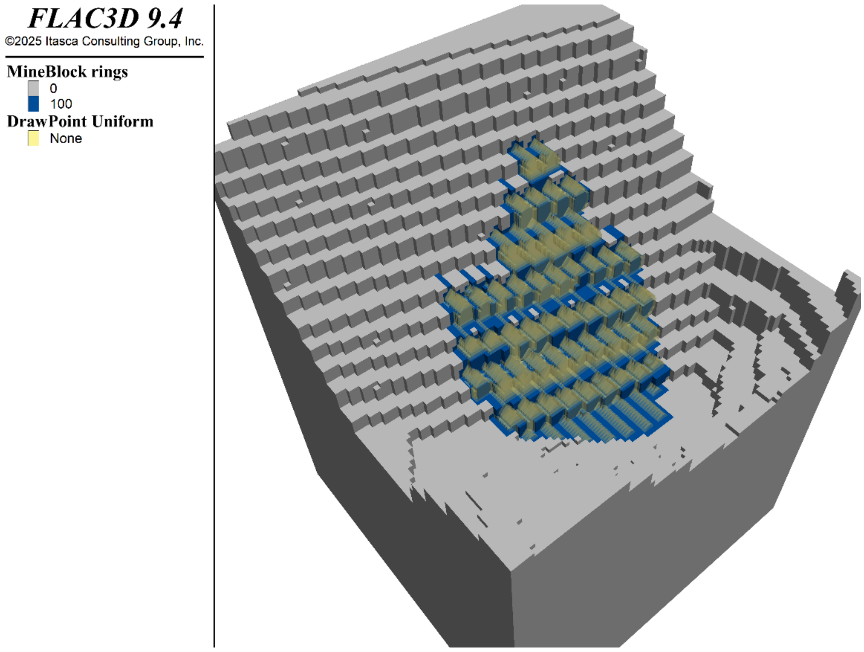

Figure 10 Isometric 3D view showing the proportion of material (blue colour) within the sublevel rings, and the external material considered as dilution (grey colour)

3 Results

The results of the study are presented for two mining stages: (1) at the end of Phase 1 and (2) at the end of life of mine. Figures 11 and 12 show the model results at the end of Phase 1 and life of mine for 15, 18 and 21 m for good and poor blasting conditions, respectively. As anticipated in granular flow theory, global recovery exhibits a strong inverse correlation with crosscut spacing. The model quantifies a recovery deficit of approximately 3–4% for every 3 m increment in spacing. This decrease in performance is primarily attributed to the reduction in drawzone overlap; wider spacings (18 and 21 m) promote the formation of IEZs, where ore remains stranded in the 'shoulders' between active crosscuts. Conversely, the 15 m spacing facilitates a more uniform flow state, which is essential for maintaining a uniform ore–waste interface and maximising primary recovery.

The influence of blasting performance (good versus poor) is most acute in the wider 18 and 21 m layouts. In these cases, restricting flow within the rings exacerbates the risk of early-entry dilution. During the early extraction phase (below 100% extraction), poor blasting results in a 1–3% recovery loss at the end of Phase 1. However, the recovery gap caused by blasting performance narrows significantly once over-extraction is completed. As mining progresses to deeper levels, the material initially bypassed or 'frozen' due to poor fragmentation is eventually mobilised and captured. This suggests that while layout geometry sets the theoretical ceiling for recovery, the ultimate extraction efficiency at Jwaneng will be heavily reliant on a disciplined draw control strategy capable of managing the transition from Phase 1 to the end of life of mine.

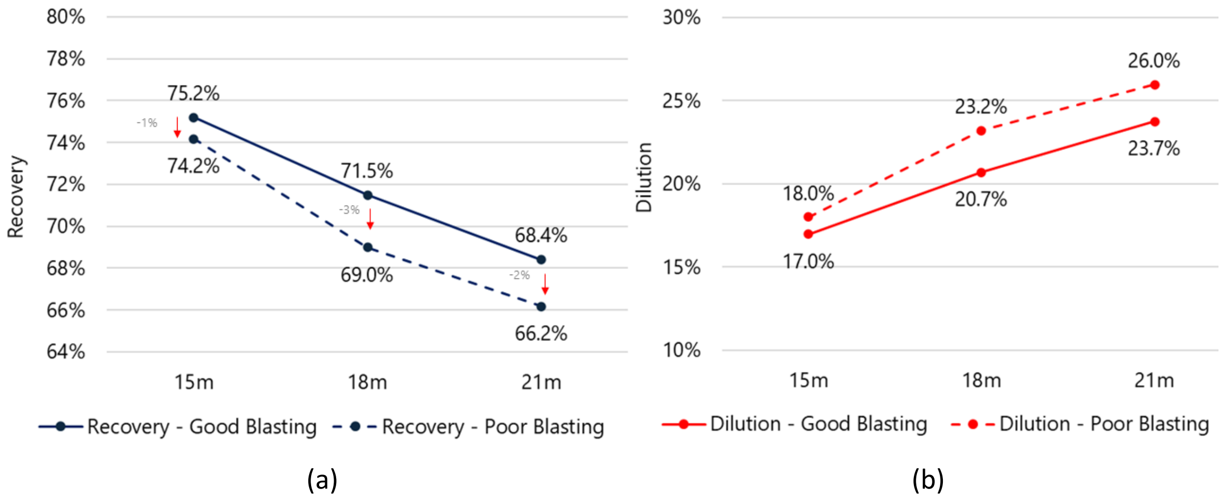

Figure 11 Model results at the end of Phase 1: (a) Recovery for 15, 18 and 21 m crosscut spacings for good and poor blasting conditions; (b) Dilution for 15, 18 and 21 m crosscut spacings for good and poor blasting conditions

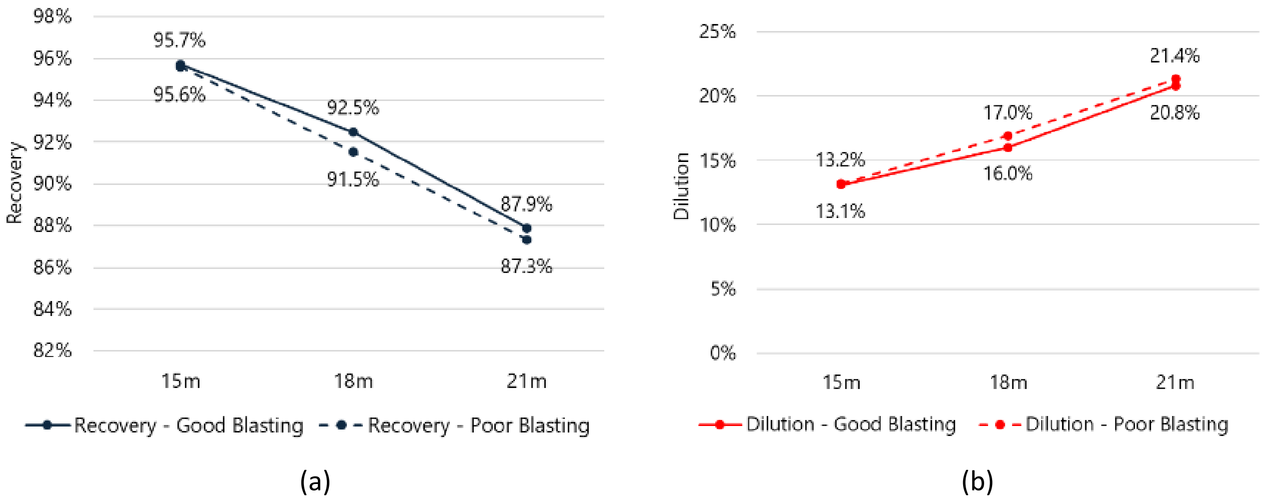

Figure 12 Model results at the end of life of mine: (a) Recovery for 15,18 and 21 m crosscut spacings for good and poor blasting conditions; (b) Dilution for 15, 18 and 21 m crosscut spacings for good and poor blasting conditions

3.1 Benchmark comparison

To contextualise the numerical results, the Jwaneng model outputs were compared against global benchmarks for SLC, sublevel retreat (SLR), and front caving operations as compiled by Campbell (2022). This comparison is particularly relevant for Jwaneng, as the performance of kimberlite pipes transitioning from open pits is heavily influenced by the nature of the mining above and the maturity of draw.

The benchmarking data reveals a distinct correlation between draw maturity and recovery efficiency, suggesting that modelling results are in line with this understanding. Figure 13 shows an ore recovery and dilution comparison between the model results and benchmarked kimberlite mines.

Operations such as Diavik (A418 and A154S, Canada) with a crosscut spacing of 15 m, which utilise SLR, typically draw to 100% in the upper horizons but encounter high dilution early in the life of mine. Similarly, Koffiefontein mine (South Africa), utilising a front cave configuration with a crosscut spacing of 19 m, shows a strategy of increasing draw intensity with depth, moving from 120% on the initial level to as high as 240% on subsequent levels. While this aggressive draw maximises recovery, it inherently accepts higher dilution as a trade-off.

In contrast, Finsch mine (South Africa), with a crosscut spacing of 21 m, represents a more conservative approach in the upper levels (66–80% draw), scaling to over 150% in later stages to achieve low dilution profiles. The Jwaneng results, which indicate a 3–4% recovery sensitivity to crosscut spacing, align closely with these established trends. Specifically, the modelled recovery at Jwaneng suggests that a disciplined draw strategy will be critical. The benchmarking confirms that for kimberlite pipes, the ‘low recovery’ often observed in early phases is not necessarily a design failure of the layout but rather a function of draw maturity, where the highest efficiencies are only materialised once a substantial ore blanket is established and over-extraction is initiated.

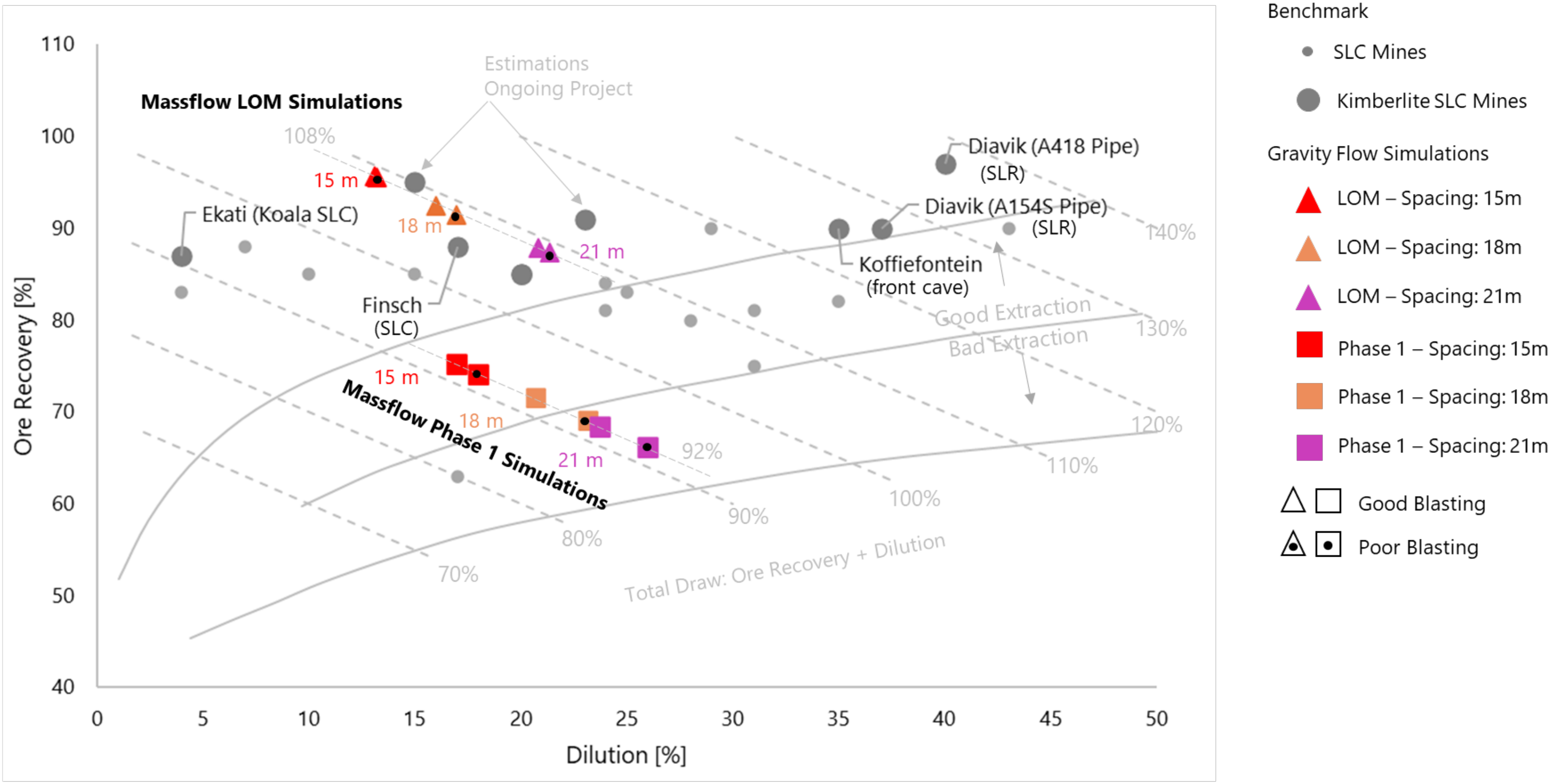

Figure 13 Ore recovery and dilution comparison between model results and benchmarked kimberlite mines (modified from Campbell 2022)

4 Conclusion

The numerical analysis of the Central pipe at Jwaneng demonstrates a clear sensitivity of mining performance to the geometric layout of the sublevel caving (SLC) design. The study reveals that wider crosscut spacing (21 m) negatively impacts global recovery as more isolated draw conditions are prevalent. As crosscut spacing increases, overlap of material flow is reduced. This in turn leads to lower recovery and increased dilution. In contrast, narrower spacing (15 m) promotes a more uniform material flow. A uniform draw promotes the sustaining of an ore blanket that minimises the risk of fine-waste percolation.

The modelling also highlights that the impact of blasting effectiveness is more pronounced during early and intermediate stages of extraction. Under poor blasting conditions (characterised by incomplete fragmentation and restricted mobilisation), dilution levels increase when global extraction is less than 100%. However, as the mine moves into over-extraction phases deeper in the pipe, much of the material initially left between rings is eventually recovered. This suggest that while wider spacing might be more susceptible to poor blasting conditions, a robust over-extraction strategy can partially mitigate early-stage recovery losses.

When compared to global benchmarks for kimberlite mines like Finsch, Koffiefontein and Diavik, the results for Jwaneng suggest that crosscut spacing is not the only key variable to a successful performance. Benchmarking data indicates that mines with identical layouts can achieve vastly different recovery and dilution results depending on their specific draw strategies and conditions. For Jwaneng, the primary design recommendation is that a narrower crosscut spacing could provide a more resilient operational framework. It offers a higher margin of error against the inherent variability of blasting in kimberlite, ensuring more consistent ore flow as the mine transitions from its current open pit to deep-level SLC.

It is important to note that these results are derived from uncalibrated numerical models; they are intended to facilitate a comparative analysis of design geometries using a consistent and standardised set of input estimates. While these trends provide a robust basis for evaluating the relative performance of different layouts, the models will require future calibration against observed performance as Jwaneng transitions to underground production. In addition to these limitations, the ring geometry (including silo versus standard configurations and shoulder hole angles), the drawpoint geometry and size, and the potential for kimberlite material compaction will likely influence material flow, thereby affecting recovery and dilution entry.

Furthermore, the selection of an optimal layout requires a balanced consideration of recovery and dilution targets against geotechnical stability. While stability is anticipated to remain within manageable limits during Phase 1, the trade-off between aggressive extraction and oredrive stability will become increasingly critical at greater depths, where the higher stress environment may require adjustments to the draw strategy.

Acknowledgement

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