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Managing selected production level complexities and outcomes in block caving

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Abstract

Block caving performance is strongly dependent on adherence to fundamental caving principles applied consistently in both space and time. Sequencing and timing are as important as the activities themselves, and deviations driven by production pressure can lead to increased cave related risks and long-term impacts to reserve recovery.

This paper discusses selected operational complexities encountered across several caving stages, drawing on industry experience and from New Afton Mine. Specific solutions are broadly presented for undercut swell management, remnant pillar recovery, drawbell blast underbreak, oversize and mudrush management, convergence and draw control, and the re-opening of collapsed drawpoints including checkerboarding and load shedding strategies. In several cases the methods go beyond what is typically found in generic design guidelines.

A detailed case study of drawpoint grade performance following convergence and re-opening events in the Lift 1 east cave is then presented. Severe convergence drawpoints delivered a median grade reduction of 34% on Au and 31% on Cu in the 5 months following re-opening, with a 2013 pre-mining personal computer block cave (PCBC) forecast and a 2022 post-reconciliation PCBC model over-predicting actual grade across the majority of the observable height of draw (HOD) range. A mechanism hypothesis is proposed to explain the observed post-reopen grade behaviour, supported by field observations, geotechnical monitoring data and an additional PCBC run in which the draw columns of severely converged drawpoints were narrowed above their HOD at closure. This narrowing reduced the divergence between modelled and actual grade for the majority of severe drawpoints assessed and identified the HOD at closure as a physically meaningful threshold for the onset of draw column narrowing. The findings demonstrate that the grade impacts of severe convergence on the extraction level persist well beyond rehabilitation and are not readily captured by standard draw scheduling assumptions but, can be reproduced by representing the converged ore column as a narrowed draw cone.

Keywords: *draw control, grade reconciliation, convergence, cave management*

1 Introduction

Block caving is an underground mining method where production is determined by the response of the rock mass to the undercutting, stress redistribution, and gravity flow of rock into blasted drawpoints. The method has been applied successfully over a wide range of geological conditions, but its performance is dependent on adherence to established principles of design, spatial sequencing, and time-dependent activities.

Greater depth and more complex conditions such as elevated in situ stress fields, variable rock masses, water, and increased seismic response typically require risk-based adaptation which usually introduce additional constraints on the mine design planned execution.

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However, these conditions should not change the principles of caving. They should rather increase the importance of applying them correctly. Innovation should support these principles, not replace them.

This paper discusses selected production level complexities in block caving that are influenced by spatial and temporal sequencing decisions, affecting cave performance and production continuity (Section 3). It further examines the longer-term tonnage and metal grade effects due to convergence in Section 4 that may remain after rehabilitation has been completed. The grade reconciliation study in Section 4 is presented to quantify one of the longer-term consequences of the convergence events described in the operational examples found in Section 3; the two sections should therefore be read as complementary parts of the same case study.

2 Spatial and time adherence to fundamental caving stages and principles

As mining progresses to greater depths and more complex conditions, there is a tendency to introduce new approaches to manage perceived technical and production risks. While varied approaches are sometimes necessary, the fundamental principles and stages of caving remain essential and should not be displaced in the name of innovation. Rather, innovation in block caving should build on these established fundamentals by adapting them to site-specific conditions, improving their application, and reducing caving-related risks. Fundamental cave sequencing and draw strategies must respond to complexity, while performing with spatial and temporal planning. Deviation from these principles is a common cause of poor performance and is most often associated with production pressures, poor planning or unexpected geological conditions.

2.1 Caving stages and risks

2.1.1 Caving stages

To successfully undercut the orebody and then propagate a cave to surface, several stages of caving milestones should be achieved (Figure 1): cave establishment, cave initiation, cave propagation, and cave breakthrough, with further descriptions and ways to determine the stages found in Kamp (2024).

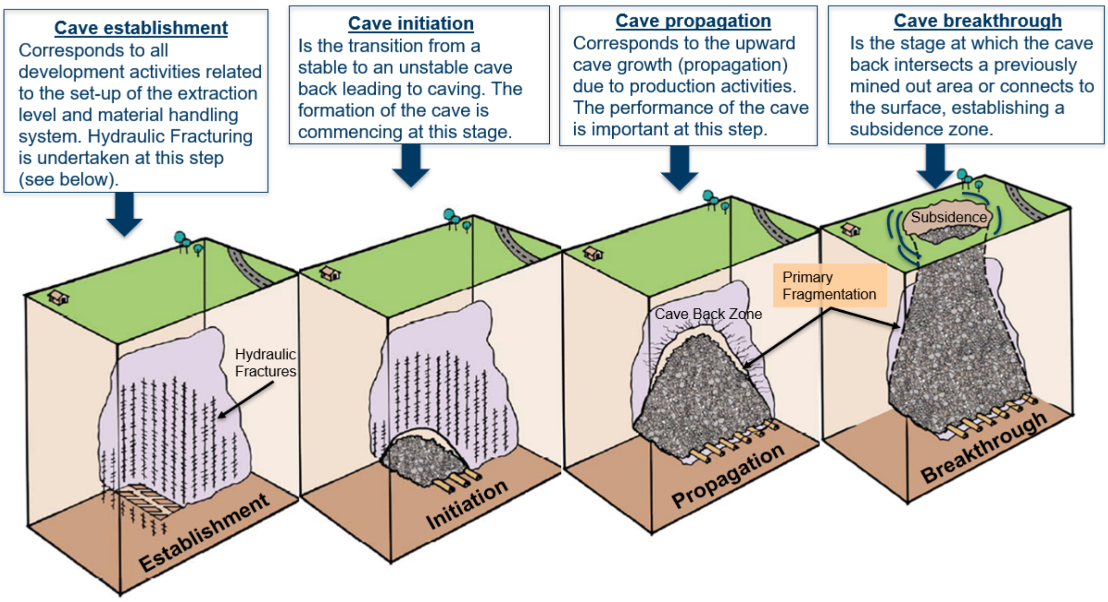


Figure 1 Four stages of caving (Cuello & Newcombe 2018)

2.1.2 Caving risks

Caving-related risks typically including mudrush, seismicity, convergence, oversize management, and cave profile performance. As these caving-related risks present themselves, the management of them is not a straightforward process. The location of where and when they are occurring can have an impact on the long-term performance of the cave. Higher priority risks require continuous monitoring and real-time response, while others are managed over longer timeframes with periodic review as seen in Table 1.

Table 1 Example of caving-related risks and management

Risk occurrence	Typical response priority
Mudrush/inrush	Real-time
Seismic	Real-time
Convergence	Weekly to daily
Oversize	Daily (by shift)
Cave profile Interpretation	Bi-weekly to monthly

This prioritisation should be supported by management plans and procedures for each risk. This includes specific risk management plans, geotechnical guidelines, and standardised operational procedures, which are maintained and updated at varying frequencies depending on the nature of the risk. The integration of these plans into draw control ensures that production decisions are informed by caving-related risks and then aligned with broader and long-term cave management objectives.

Once the cave is established, the production footprint offers very limited opportunity for correction. Errors in spatial and temporal design are carried through the life of the cave and can remain a challenge over extended periods of cave operation. Although the resulting risks may be managed or operationally stabilised, longer-term impacts to tonnage recovery, reserve extraction, and metal grade performance are difficult and costly to reverse.

To manage these risks, caving principles and best practices must be consistently applied throughout the life-of-mine. While a caving schedule can be planned in mine planning software with set targets such as bells blasted per month or tonnes per day, there will be additional operational complexities that arise. These complexities may initially present as schedule delays and subsequent management concerns, but more importantly they impact the timing and location of key tasks, which can lead to caving-related risks if the underlying principles of even draw, timely undercut advance, and controlled re-opening are not maintained.

2.2 Caving principles

Caving literature emphasises an adherence to established principles for all stages of the caving process. These principles must be applied both spatially and temporally, not as independent considerations. When and where each activity is executed is just as important as the activity itself. These are separate from design parameters best suited to the orebody, such as pillar spacing, ring burden, drawbell design, tunnel size, explosives selection, ground support, and equipment selection. The focus of this discussion is on the operational and scheduling principles that govern when and how caving activities are sequenced.

The term 'caving principles', or similar, is widely used in the industry to describe the suite of rules, guidelines, and best practices that govern how a block or panel cave is designed and operated. In practice, while this body of knowledge is a set of derived first principles that follow the standard methods (Laubscher et al. 2017), the reality is that caving principles are also a compilation of lessons learnt: hard-won experience accumulated from decades of cave mining at operations around the world. Modern publications from symposiums continue to expand and refine these principles in response to deeper, higher-stress, and increasingly complex operations. A short and basic literature review is provided in the Appendix, reflecting the importance of applying caving principles both spatially and temporally.

2.3 Spatial and temporal considerations

In practice, the spatial and temporal cave engineering elements are often imposed by orebody shape and the resources available. In such cases, the design must recognise the limitations and allow for them. The objective is not to achieve a technical perfect layout, but to maintain the integrity of the cave by following spatial and temporal best practices. The Appendix provides a simple reference list of spatial and temporal practices along with documented caving risks and operational complexities if not managed accordingly. These are all taken from reference papers and broader literature and do not cover all the available sources, but act as initial references. Additional examples of selective operational complexities and solutions from the New Afton Mine are discussed in Section 3 which then leads into the grade performance observations after the repair is completed specifically for when convergence is encountered on the production level.

Spatial decisions define where caving activity occurs in relation to the orebody and the surrounding rock mass. These include the undercut initiation location, cave front geometry and direction, orientation to principal stresses, drawbell sequencing, and production draw priority. Together, they shape where and how the rock mass responds through the caving stages, and long-term reserve recovery.

Temporal decisions define when and how fast caving activity occurs in relation to the response of the rock mass. These include the undercut advance rate, swell removal timing, drawbell blasting rate, and the production rates used during the lifecycle of the cave extraction. They must remain aligned with the evolving stages of cave development and the response of the rock mass.

3 Discussing selective operational complexities and solutions

Block caving operations encounter a broad range of risks and complexities across the mine life. This section does not attempt to cover every caving risk in detail, but rather focuses on a selected set of operational complexities, drawing on experience from New Afton Mine. Specific solutions are broadly presented for undercut swell management, remnant pillar recovery, drawbell blast underbreak, oversize and mudrush management, convergence draw control, and the re-opening of collapsed drawpoints including checkerboard and load shedding strategies. In several cases, the methods go beyond what is typically found in generic design guidelines.

3.1 Undercutting and cave front management

3.1.1 Undercutting location and mucking swell

The temporal and spatial management of undercutting along with the supporting development determines how stress is redistributed ahead and around the cave front. A poor choice of initiation location, blasting, or rapid or uneven advance, can lead to stress concentration, convergence, seismicity, and airblast. Each undercut blast should be respected to ensure they have been blasted to their intended design and that enough swell material has been mucked before firing the next blast.

Undercut swell is pulled to ensure sufficient void is available for caving to start and continue. If too little swell material is pulled, or if the time between an undercut blast and mucking the material out through a drawbell is extended, larger rocks may consolidate on the blasted undercut material, reducing the intended interaction between the production level drawpoints and the undercut. To prevent this, when mucking the undercut blasted material, 40–60% should be removed to confirm breakage and create void for the next ring to blast into. In addition, for longer anticipated times between undercutting and bell blasting below in a pre-undercut or advanced undercut, a preference to a higher mucked percent should be considered to allow for additional void space as more time is needed between the undercut blast and drawbell blast below, and this would be done to potentially reduce consolidation of the undercut blasted rock.

Timing of how the swell is mucked is also important to ensure material is behaving as expected to support the next ring blast and to make sure no incomplete previous undercut ring blasts are present. In the example provided in Table 2, within 36 hours of blasting a set of undercut rings, 20% draw (~660 t or 54 buckets) must be taken to verify that the blast was fired, which confirm breakage of the back breaker holes. If the undercut ring will be idle for more than one week due to sequencing requirements, about 4% or 10 buckets per week should be taken from the ring to minimise standing time. In the week prior to blasting the next ring the remaining tonnage (up to the 50% total target) should be taken (or more if the operation deems higher pulls are warranted), with at least 9–10% being mucked within 24 hours of the planned blast. Ring designs are also given to the operators with minimum spatial requirements for loading lengths.

Table 2 Example of managing undercut swell at New Afton Mine where the target is 50% in the example

Undercut muck time dependency tasks	%	Tonnes (t)	Number of buckets (~12 t)
Total blast	**100**	**3,300**	**270**
Draw target (40–60%)	50	1,650	135
- Post-blast (36 hours)	20	660	54
- Idle draw (per week)	4	122	10
- Pre-blast (week)	17	868	71
- Pre-blast (24 hours)	9	306	25

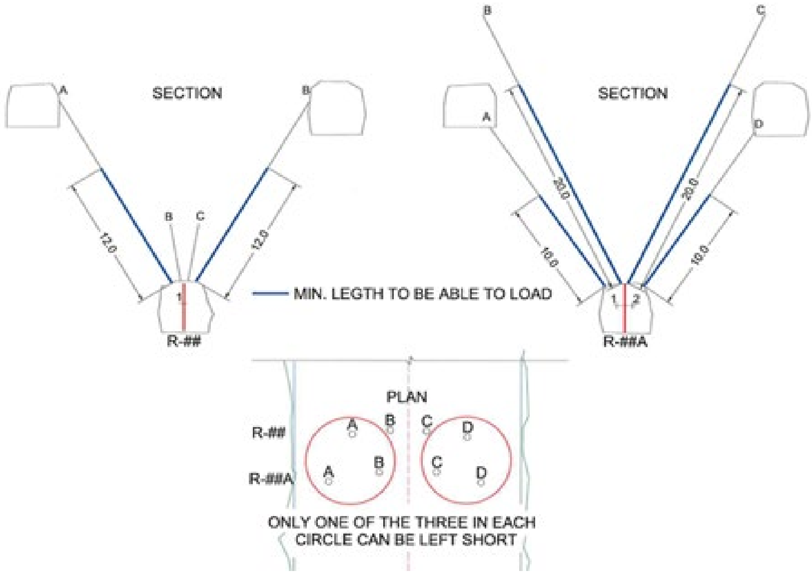


Figure 2 Ring design with spatial requirements for loading

Undercut management is critical to make sure proper tonnages are being pulled as this sets up the success for the drawbell. Also, in many cases for pre-undercutting and advanced undercutting there may be a desire to pull more undercut tonnes for production targets. This needs to be managed as there is a possibility for air blast risk. During caving post-critical hydraulic radius along the advancing cave front, there is also the potential of cave propagation material entering the undercut, and this is why additional buckets should be mucked prior to initiating the next blast to have an appropriate free face.

3.1.2 Undercutting remnant pillar recovery

Incomplete undercutting and the formation of remnant pillars or bridges can occur and can have severe consequences for both the undercut and the extraction level below, as these features concentrate and transfer point-load stresses from the cave (Figure 3). If pillars do form, they should be removed immediately prior to blasting subsequent undercut rings to prevent stress build-up and associated damage.

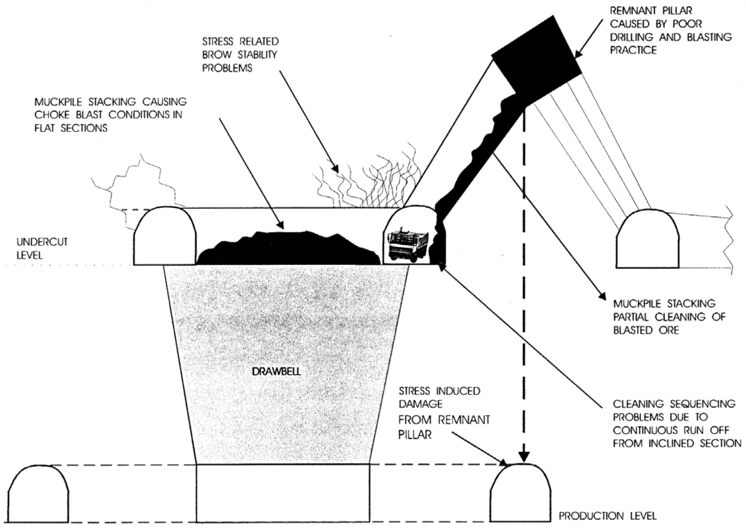
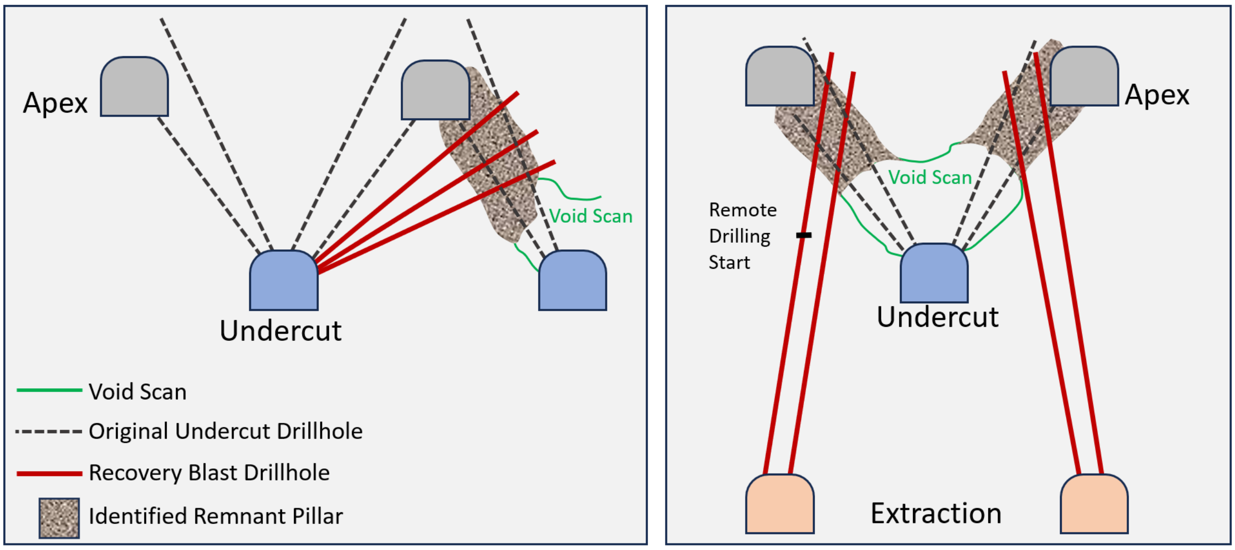


Figure 3 Potential point-loading or stress-induced damage of the extraction level due to the formation of a remnant pillar in an inclined undercut (Butcher 2000)

To prevent this, breakage between undercut drives must be confirmed. Visual verification from the undercut brow exposes personnel to elevated risk from falling and riling rock and should be avoided where possible. The use of an apex level provides an observation platform to assess the effectiveness of the undercut blast. Cavity monitoring surveys (CMS), boom-mounted cameras, and drones allow for inspection while minimising personnel exposure.

When an undercut blast issue has been determined, there are a few options for drilling and blasting which depend on the lead/lag of the undercut status and extraction level access. Figure 4 below shows several options for blasting out an identified remnant pillar either from the undercut level, or by drilling from the extraction level. It is also important to immediately blast any remnant pillars so the success can be measured by re-scanning or observations. Records should be kept to better understand the success of the undercut blasts and to note if any issues were encountered. Holes at New Afton are typically drilled up to 34 m long with a Sandvik DL420 using a 104 mm drill bit and loaded with emulsion with airbag stemming, and collar grouted to prevent damage to the production level during the blast.



(a) (b)

Figure 4 Solutions to remnant pillar blasting. (a) Drilling recovery holes from the neighbouring undercut drift if lead/lags allow; (b) Drilling recovery holes from the extraction level

3.1.3 Undercut and cave front shape and rate

During the cave initiation stage as the cave begins to propagate, in situ stresses are redistributed by the caving process and the cave-induced abutment stress in the cave front is controlled by the progression of undercutting and development of new drawbells. This can be managed by choosing the location of where undercutting is being completed, maintaining undercut advancement rates, drawbell production rates and also recognising geological influencing factors such as how to undercut through a fault or weaker lithology by adjusting the rate, the face angle or sequence.

Undercut advance rate is controlled by a combination of operational and geotechnical constraints. Key factors include the size and geometry of the mining footprint, where smaller or irregular undercut faces may limit productivity, the height of the undercut which influences drilling and loading times, and geotechnical conditions such as seismicity, pre-fracturing requirements, and ground quality which can further restrict the achievable rate of advance. In addition, stress-induced damage within the undercut front can limit progress through issues such as poor hole performance, blasting inefficiencies, restricted access, and localised convergence or collapse. The selected undercutting method, whether post-undercut, pre-undercut, or advanced undercut, also impacts the achievable rate of advance.

The continuity of undercut advance is critical. Stopping the undercut in any location for a prolonged period allows abutment stresses to remain at a set location, increasing the likelihood of damage to both the undercut and extraction levels. To manage this, clear limits on allowable standing time should be defined prior to initiation. In practice, standing times should be limited to the order of 2 weeks to a couple months maximum, depending on rock mass strength, location, and stress conditions.

Industry data indicates that undercut advance rates average approximately 2,000 m² per month when expressed as the plan area blasted above the production level (Figure 5). However, monthly advance curves provide better insight into ramp-up behaviour, peak rates, and periods of reduced activity. Variability in advance rate is acceptable, as observed in Figure 5, provided that changes occur over timescales shorter than the rate at which damage accumulates in the rock mass. Such variations should be planned or clearly communicated to the technical team to allow for appropriate monitoring and response.

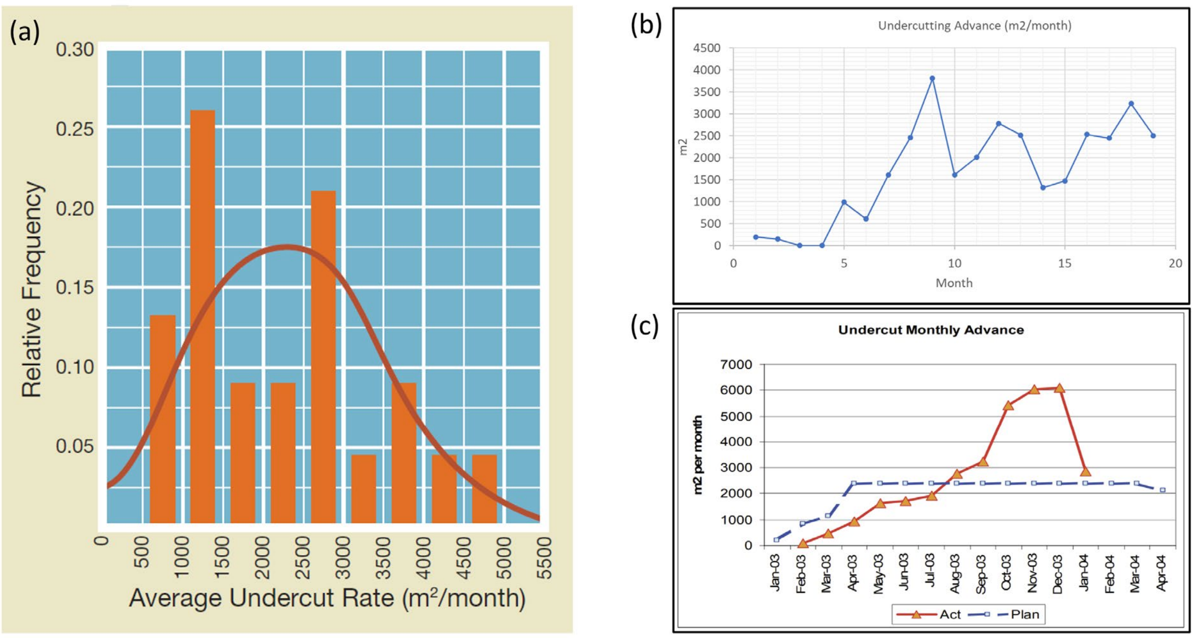


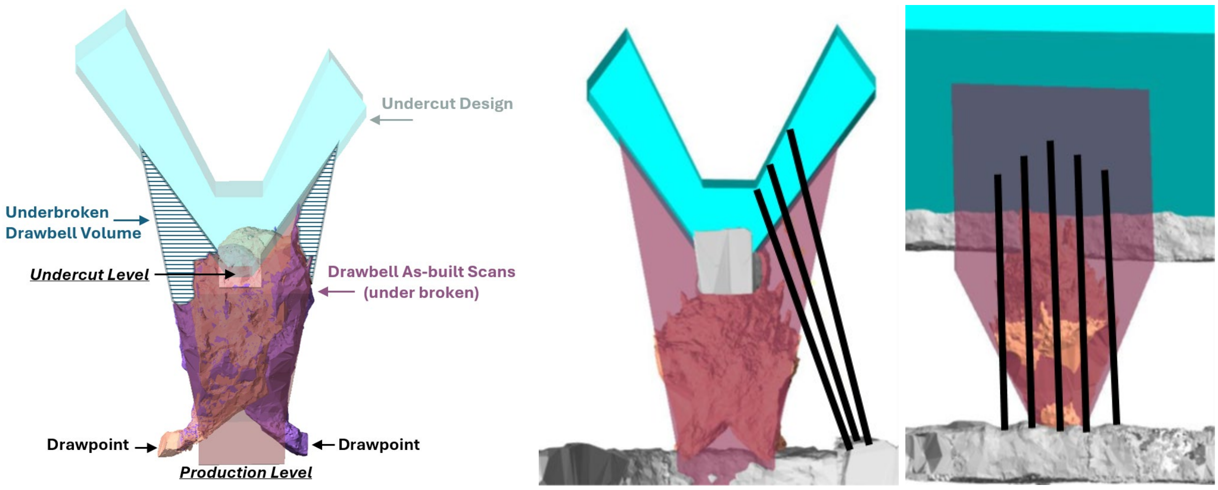
Figure 5 Undercutting rates taken from (a) Laubscher et al. (2017), (b) New Afton B3, and (c) Northparkes (Ross 2008)

3.2 Drawbell blasting, location and timing of production start-up

3.2.1 Drawbell blasting

Drawbell tonnes should be pulled to verify the bell blast went according to design. For pre-undercutting and advanced undercutting, this is done by mucking swell after the blast typically referred to as OTI (open to inspection) mucking, which is the calculated total bulked volume of the drawbell blast rock mass and the undercut remainder swell material reporting to the drawpoint brow. If the drawpoints of the drawbell pull open in a pre-undercut or advanced undercut, or there are indications while mucking that there was poor blast performance, a CMS is used to assess the need for recovery drill blasting efforts. In a post-undercut, the bell is already blasted before the undercut.

This is specifically important during the pre-HRcr (critical hydraulic radius) cave initiation stage as only light mucking (tickle tonnes) is typically done until the cave begins to propagate and the risk of airgap is reduced, therefore a bell blast problem may go unnoticed for an extended period of time until production begins to ramp-up (Figure 6). It's important to ensure that the drawbell has been blasted correctly and correct any design changes early in the construction of the footprint. In single blast drawbells, there is not a lot of void space for the blast to break into, and there is a risk that the flanges of the drawbell do not break out correctly if the blast timing is not well understood. If this occurs, recovery blasting should be conducted and a review of the drawbell blast timing between delays, number of holes, and sequence of blasting should be reviewed. In this case shown to solve the drawbell blasting underbreak, blasting modifications were made (Ierino et al. 2026).



(a) (b) (c)

Figure 6 (a) Underbroken drawbell blast, recovery blast drilling holes drilled up from the production drive; (b) Looking perpendicular to the drawbell drive and drawpoints; (c) Looking parallel to the drawbell drive

The example provided was a successful recovery using 102 mm holes from the undercut spaced at 2.5 m apart, loaded with emulsion, with a burden of 1.5–2.0 m, depending on the number of rings with required angles to drill through more competent ground using different azimuth and dip orientations, and will need to plan around any existing unblasted holes. While the drawbells were recovered, several attempts of blasting were needed, in addition higher hang-up frequency was observed at these drawpoints. Further information is found in Ierino et al. (2026).

3.2.2 Drawbell blasting spatial location and sequence

A steady rate of drawbells being blasted in a timely and consistent manner is important for caving front advance and in general it needs to align with the undercutting rate. This rate also supports the management of the abutment stresses in the advancing front of the cave and allows production to break up the rock mass above the undercut and newly blasted drawbells. The location and timing of new drawpoints is important to maintain. Experience shows an even or slightly rounded or chevron shape of the cave front is ideal, in combination with avoiding high draw differentials from previously blasted drawbells. Blasting drawbells too quickly may disrupt sequencing in the continuity of breaking up the ore in the cave front. Blasting and mucking drawbells too slowly delays cave propagation, and increases the sitting time or consolidation of the above undercut material.

Sometimes blasting a number of drawpoints becomes a mine-related target. Typically, a drawbell metric is related as number of drawbells blasted per month. Common planned numbers at New Afton typically range from lower end 3 to upper end 7 drawbells per month for an advancing cave front. It usually takes about 3 months of development, construction, and drilling tasks for each drawbell. However, the number of bells blasted is also constrained by the undercutting progress for advanced and pre-undercut. And for post-undercut blasting, too many bells in advance of the undercut may result in local air blast risk and unwanted abutment stress impacts.

3.2.3 Drawbell production start-up

Production draw rate typically governs caving rate; the best practice is to initiate draw relatively slowly following undercutting and ramp-up gradually to steady-state production to avoid cave related risks. van As & Guest (2020) attribute the formation of irregular cave shapes primarily to the way the cave is drawn. This staged or gradual ramp-up allows stresses in the cave back sufficient time to fracture and fail the rock mass above the cave back across the full extent of the footprint.

During ramp-up and prior to cave breakthrough, the draw rate must remain below the cave propagation rate to prevent the formation of an airgap and to ensure adequate fracturing of the rock mass through stress-induced and gravity mechanisms.

Based on experience, Table 3 provides a guide for cave draw rates as a function of the orebody fracturing. These rates are indicative of New Afton operating conditions and should be calibrated to site-specific rock mass, stress, hydraulic, fragmentation and cave-propagation conditions before being applied elsewhere. If caving-related risks are observed, the draw schedule should be adjusted with the cave monitoring systems to guide decisions.

Table 3 Indicative drawpoint production plan for stages of caving

Drawpoint maturity	Tonnes of draw/day/drawpoint
Prior to HR_{cr} and drawpoints less than 3 months	50–60
Post HR_{cr} and 3–6 months	60–100
6–9+ months	100–120
Continuous caving/propagation stage	120–200
Steady production pre-breakthrough	150–300+
Post cave break-though/steady-state production	200–350+

3.2.4 Drawbell production oversize and mudrush

Managing oversize can become an issue when trying to get the cave from construction to propagation and then maintaining steady mucking. The requirements to manage oversize are typically a water cannon, a rock breaker mounted on a production scoop, or a drill and blast solution. To maintain production continuity, an on-shift drill and blast procedure should be developed to manage oversize without having to wait in between shift change to keep drawpoints flowing.

In some cases, the operation may have oversize early in the mine life and as the cave matures, the frequency becomes lower. However, in other cases, it’s something that remains relatively consistent over time and will need to be managed. For example, New Afton Lift 1 and B3 caves secondary breakage events are plotted where Lift 1 progressively declined in oversize occurrences, while B3 started with less oversize but showed no declining trend, but maintained relatively low occurrences of oversize (Figure 7).

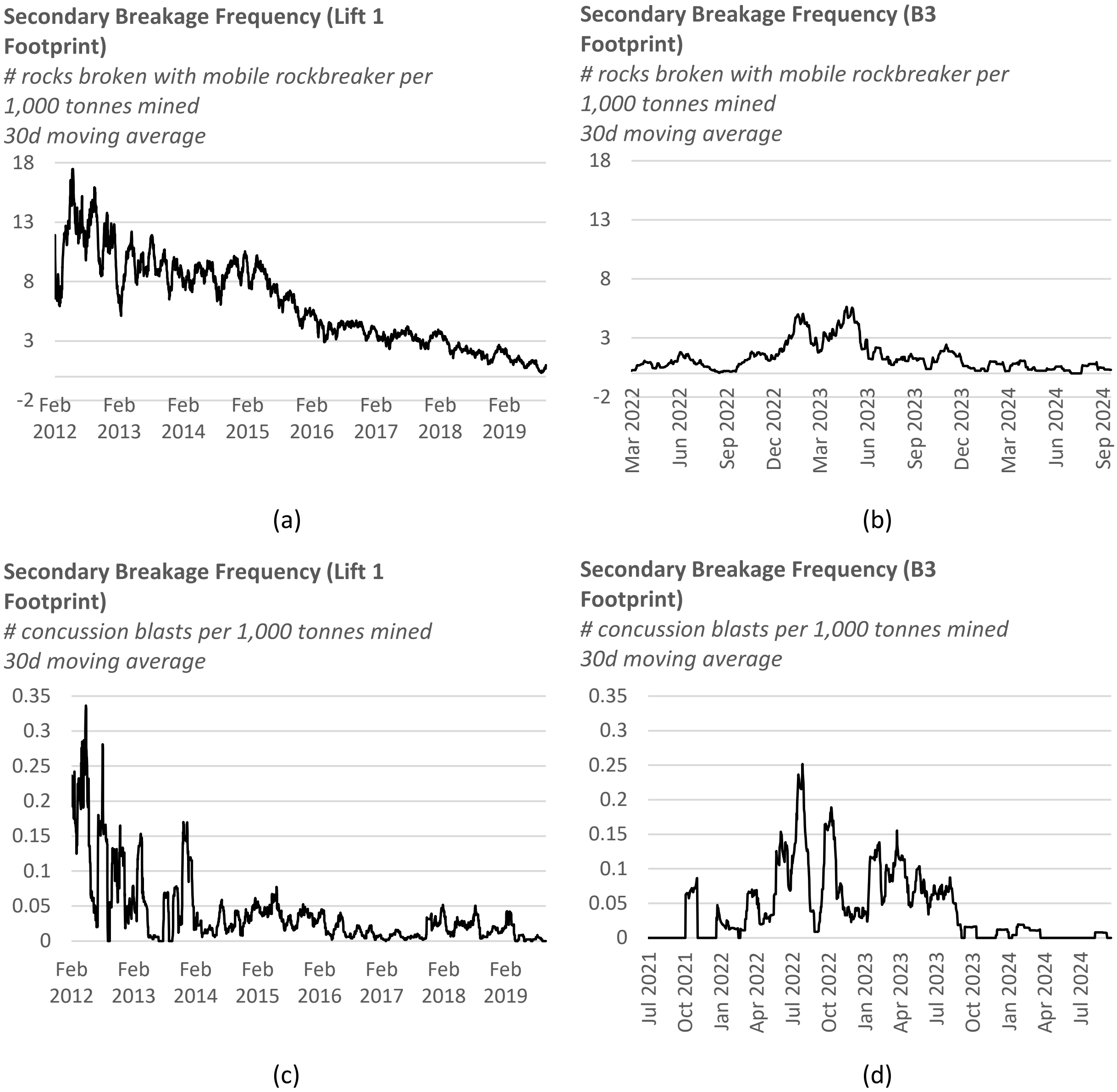


Figure 7 Secondary breakage frequency, number of rocks broken with mobile rock breaker per 1,000 tonnes mined, 30 day moving average for (a) Lift 1 and (b) B3. Number of concussion blasts per 1,000 tonnes mined for (c) Lift 1 and (d) B3

When mudrush events are occurring, the draw management typically focuses on the operational safety of managing the exposure of personnel and equipment. This may include transitioning to remote mucking operations when mudrush risk becomes too elevated for personnel to safely work at the drawpoint, which in turn limits the ability to maintain consistent draw rates and even cave advance and requires temporal limitations on when a drawpoint can be mucked as seen in the example below, where ~30% of the recorded mudrush events occurred up to 10–11 hours after mucking of the drawpoint took place (Figure 8). The effects of mudrush on production and grade performance are complex and multifaceted, and while noted here as a significant draw control constraint, a full review is outside the scope of this paper.

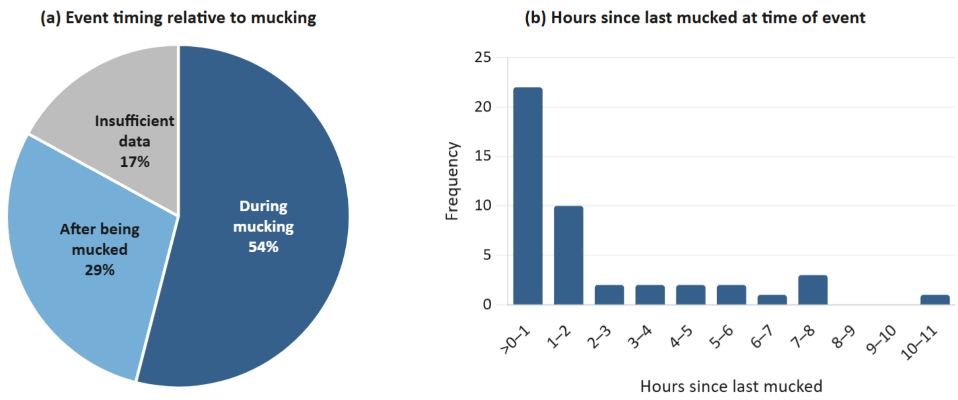


Figure 8 **Timing of mudrush events at New Afton Mine relative to mucking activity. (a) Event timing relative to mucking; (b) Hours since last mucked at time of event**

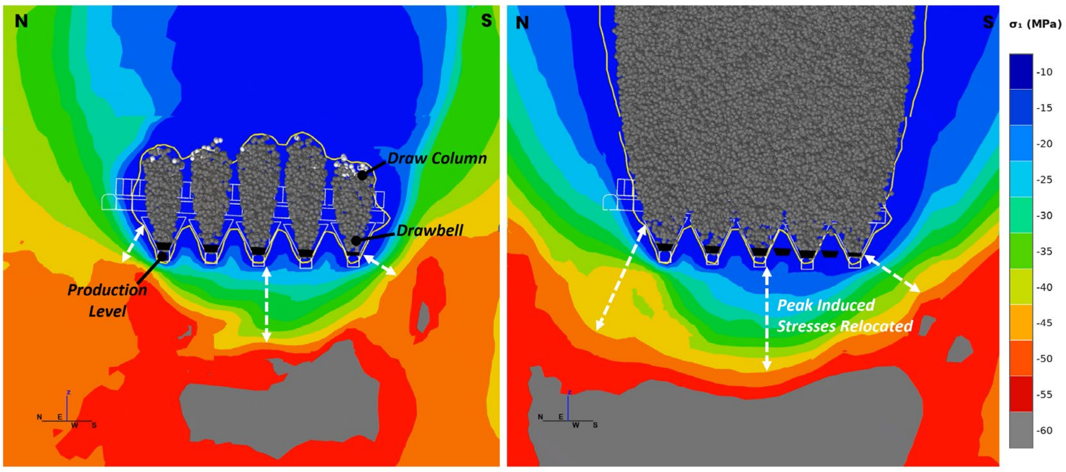
3.3 Drawpoint production for induced stress, convergence, loadshedding and re-opening strategies

Convergence on the extraction level can result from abutment stresses during cave initiation, from uneven draw creating differential loading across the muckpile, or from undercut continuity issues, as discussed in Section 3.1.2. Once the cave is in production, draw control is the primary means available to manage and respond to convergence. This section discusses strategies for managing production from drawpoints to reduce convergence risk, including load shedding approaches and the re-opening of collapsed drawpoints.

3.3.1 Drawbell production timing: abutment loading

The spatial and temporal interaction between drawpoints is fundamental at all stages of caving. The cave responds to the combined effect of interactive draw control across the footprint to manage and maintain the redistribution of caving induced stresses.

For the edges of the footprint, where the undercutting and drawpoint boundaries remain fixed, there may be abutment loading conditions affecting the production level leading to convergence due to the cave-induced stress abutments wrapping tightly around the footprint. The only way to manage this is to propagate the cave through production so that the lateral extent of the cave profile begins to widen out and redistribute the stresses laterally, essentially stress shadowing the production level perimeter (Figure 9). This may become more of a longer-term issue with narrower footprints than wider footprints.



(a) (b)

Figure 9 **Modelled principal stress (σ_1) illustrating the redistribution of cave-induced stresses between (a) cave initiation and (b) cave propagation as the cave grows laterally and vertically**

Another design change is to use half drawbells (Figure 10), which can reduce the induced stress risk to perimeter strikedrives and will also increase the hydraulic radius potential to promote the cave initiation for narrow footprints.

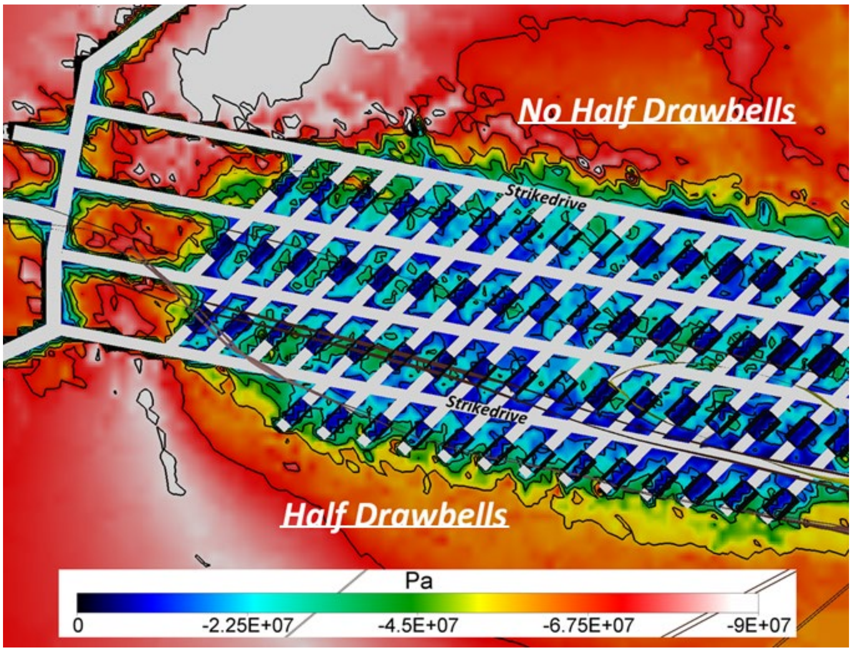


Figure 10 Benefits of adding width by adding half drawbells to reduce the induced stress on the strikedrive during caving (Beck 2017)

3.3.2 Drawbell production cave loading

The timing of production from drawpoints needs to be consistent for the life-of-mine, it is ideal to keep production from drawpoints constant once it is blasted. Once the undercutting process has been completed and the drawbell has been handed over for production, it remains subject to the weight of the overlying caved material. Although these stresses are lower than the abutment stress, the extraction level is more vulnerable at this stage due to higher extraction ratios as the apex pillars are no longer confined by the rock mass and may have also experienced damage incurred during abutment loading cycles from undercutting and drawbell blasting and may be within poor geological conditions or areas of larger span due to overbreak. The extent to which muckpile load is transferred to the extraction level, and how this varies with muckpile height, is not very easily measured making it difficult to make engineering responses to. While instrumentation or scanning techniques of the extraction tunnels can be completed to measure convergence, it is difficult to fully monitor the cave muckpile height/weight above each drawpoint to fully understand the material vertically loading a specific drawpoint. Pierce (2019) used a limit equilibrium approach combined with Monte Carlo simulation to forecast the vulnerability of deep block and panel cave extraction levels to convergence under cave-induced loading. The analysis, presented in nomogram form, indicates that severe squeezing risk does not increase indefinitely with mining depth due to arching effects, but is primarily controlled by draw control quality, drawpoint availability, and the hydraulic radius of the active draw area. The only way to manage convergence on the production level is through strict and shift-to-shift production management.

3.3.3 Production convergence management

When convergence is occurring within an extraction level drive, time and location-based criteria for mucking can be considered to attempt to increase the muckpile porosity and reduce stagnant cave loads or abutment stresses, similar to that proposed in Figure 11. This method is a conceptual approach developed from operational reasoning and observations at New Afton, and would benefit from further field trials to validate the tonnage and HOD thresholds that reduce convergence rates.

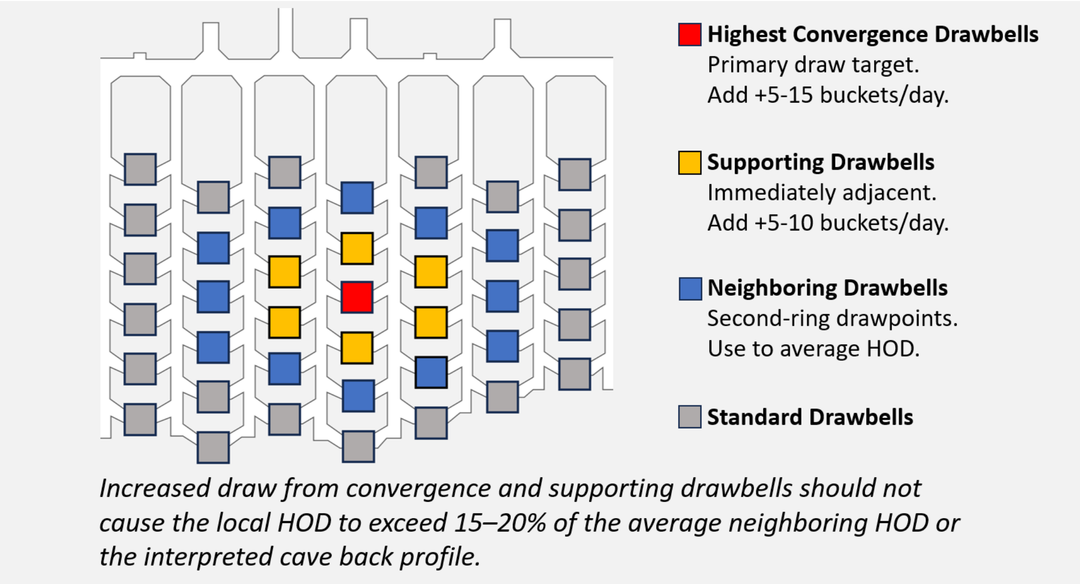


Figure 11 A proposed plan example for draw control management of convergence

In this example, the highest convergence drawpoint is the drawpoint undergoing convergence deformation, which is typically visually observed or by using scan data or extensometers. The supporting bells are the drawbells around the area of convergence, and the neighbouring bells are used for determining HOD calculations. This plan would be executed by increasing production from the converging drawpoint and the neighbouring drawpoints, with a focus on the drawpoint/s seeing the most convergence. The increased tonnages within the convergence and supporting drawpoints should be determined by the geotechnical and draw control group, but ideally all production should be issued so this area is pulled uniformly over a short duration within 12-hour shift. This is done to promote creating porosity of the muckpile by breaking up the load within the area under convergence. The load shedding strategy should be maintained until the risk is mitigated, defined as convergence rates decreasing to less than 1–2 mm/day or otherwise determined by the geotechnical group.

To ensure that the increase in production does not cause a new issue of cave profile geometry or reporting water, the HOD at the convergence location should not exceed a set target (e.g. +15% of the neighbouring drawpoint average HOD or alternatively +15% of the ideal cave back determined using instrumentation).

3.3.4 Re-opening collapsed drawpoints

In drawpoints that have collapsed or require rehabilitation and then are fully repaired, it is critical that production becomes a priority to re-establish draw. Priority systems should rely on the spatial and temporal actions of production mucking. Typically, converged drawpoints experience a compacted muckpile and become difficult to re-establish as the column behaves much narrower than design (Cancino & Kamp 2022). Once the ore column flow is re-established, a controlled ramp-up in mucking should be implemented, and as a secondary measure, a load shedding strategy (Figure 11), including adjacent and nearby drawpoints to support sustained flow conditions to improve porosity of the cave load above. Following reconnection to the cave, after the converged and sometimes consolidated muckpile is mobilised, based on experience, convergence rates are expected to decrease as regular production mucking is maintained. If a drawpoint is re-established after rehabilitation but not placed into sustained production, elevated convergence rates are likely to reoccur and the drawpoint will re-collapse. Historically, about 200–250 tpd was set as a goal in Lift 1 at New Afton Mine (Kamp 2022) to maintain convergence rates in areas that were previously completely collapsed and re-opened for production. A table of before collapse and re-opening after collapse until successfully grade depletion can be seen below (Table 4). The table illustrates the importance of maintaining higher production throughputs in areas where convergence is occurring.

Table 4 Drawpoints closed due to collapse, re-opened and mined until depletion

Drawpoint	Tonnes per day when collapsed			When the drawpoint collapsed	Tonnes per day when re-opened and remained open			Additional tonnes after re-opening
	Average	Min	Max	Tonnes (Kt)	Average	Min	Max	Tonnes (Kt)
D29S	45	4	134	36	151	55	245	73
D30S	40	1	76	32	173	27	265	93
D32S	40	6	74	29	201	86	289	110
D31N	52	23	141	35	171	53	352	61
D34S	57	18	118	32	236	119	374	181
C32S	44	0	93	33	229	125	323	113
D33N	61	40	164	35	269	130	373	136
F39S	34	14	104	32	155	98	240	84
C34S	50	0	117	35	224	46	415	258
F40N	38	4	80	12	234	105	408	188
G40S	35	0	250	18	123	106	134	17
F41S	36	2	101	10	132	68	217	107
G41N	41	0	87	21	120	100	161	30
F42N	32	18	69	6	148	8	247	154
G43N	47	14	95	17	106	93	120	24
F44S	59	0	165	8	112	60	141	30

3.3.5 Convergence exceeding the rate of rehabilitation

When convergence is exceeding the rate of rehabilitation or when the rates of deformation are beyond the ability to support, areas may be closed with the intention of re-opening at a later stage. While it is unfortunate to experience, there are several solutions that may work. If it is safe to do so, filling in drawpoints or production drift tunnels with concrete will help reduce volumetric bulking of the rock mass around the excavations. Experience shows that production muck or oversized material does not work alone; it must be tight filled and preferably poured or pumped concrete of high strength to align with the production drift. Convergence may reduce or halt over a duration of time, typically after the cave loading has had time to redistribute. Once this is completed and the surrounding areas do not show convergence deformation, then rehabilitation can take place in a planned sequence; however, the rates may start to increase if the drawpoints are not rehabilitated and mucked in a favourable sequence (Kamp 2022).

If the rates of convergence in the production drive become stable once all the drawpoints have been concreted closed, then through careful monitoring and support methods, the drawpoints can be re-opened. In some cases, it might be best to re-open every second drawpoint to maintain stability, then pursue the re-opening of the drawpoints between if the conditions allow. The drawpoint re-openings should be done closest to the active caving portion of the footprint. This checkerboard method was successfully used at New Afton Mine to recover reserves from several areas that had previously collapsed (Figure 12).

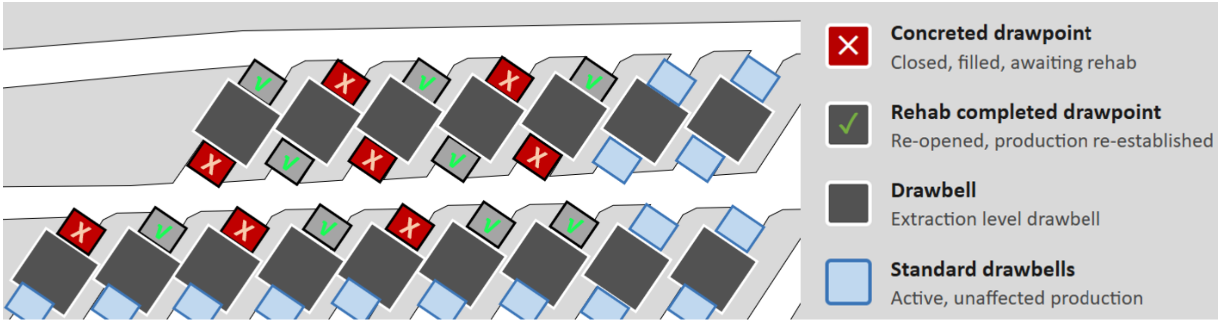


Figure 12 Example of using a checkerboarding method to re-open areas of previous collapse

The operational examples in Section 3 illustrate how spatial and temporal deviations from caving principles can create consequences that are difficult to fully reverse, with effects that can persist across the full production life of affected drawpoints. Section 3 focuses on preventing and managing convergence events as they occur. Section 4 examines one category of those longer-term consequences in detail: what happens to metal grade recovery after a drawpoint has been successfully rehabilitated and returned to production following severe convergence. The findings have implications not just for draw control practice but for how grade models are applied in planning and reserve reporting at operations that have experienced significant convergence events.

4 New Afton Lift 1 reconciliation: case study

4.1 Lift 1 (west and east caves) reconciliation

At the whole level-scale, Lift 1 reconciled exceptionally well against the pre-mining 2013 PCBC, which formed the basis of the published mineral reserves reported under NI 43-101 (New Afton 2013). A comparison of the 2013 reserve estimates against actual production at end of mining in March 2022 is presented in Table 5. Actual tonnes mined were 1.8% below the model, while Au grade came in 1.9% above and Cu grade 1.0% above, resulting in contained Au within 0.1% of the 2013 forecast and contained Cu within 0.8%. These variances are exceptional for a block cave operation of this scale and complexity. While individual drawpoint grade performance was significantly impacted by convergence and rehabilitation events (approximately 45% of the east cave footprint and 25% of the west cave footprint), the mine plan was delivered as projected in 2013.

Table 5 2013 personal computer block cave (PCBC) reserve versus actuals for Lift 1 mining

All Lift 1 (west and east cave)	Tonnes (Mt)	Au (g/t)	Au (koz)	Cu (%)	Cu (Mlb)
Actual	48.0	0.59	907.4	0.85	894.9
2013 PCBC (full model)	48.9	0.58	906.4	0.84	902.4
Variance (actual minus 2013 PCBC)	-0.9	0.01	1.0	0.01	-7.5
Variance %	-1.8%	1.9%	0.1%	1.0%	-0.8%

However, while the level-scale reconciliation was satisfactory overall, rehabilitation increases mining operating costs and introduces grade prediction uncertainty at the individual drawpoint level. When examined at a finer spatial scale, both the West and East caves show areas of localised over and under performance against the 2013 model, which are masked by the collective Lift 1 result. A detailed evaluation of the east cave has been completed to further understand the complexities of convergence re-opened drawpoints.

4.2 Drawpoint grade performance after re-opening

4.2.1 Assumptions and methodology used

Several drawpoints were closed and then re-opened at New Afton in the Lift 1 east cave. These drawpoints were classified into 3 groups: severe convergence (n=19), mild convergence (n=7), and standard re-openings (n=15). Closure durations ranged from 4 to 40 months with an average of 13 months. A control group of 83 continuously producing drawpoints provides a HOD-matched baseline throughout (Figure 13).

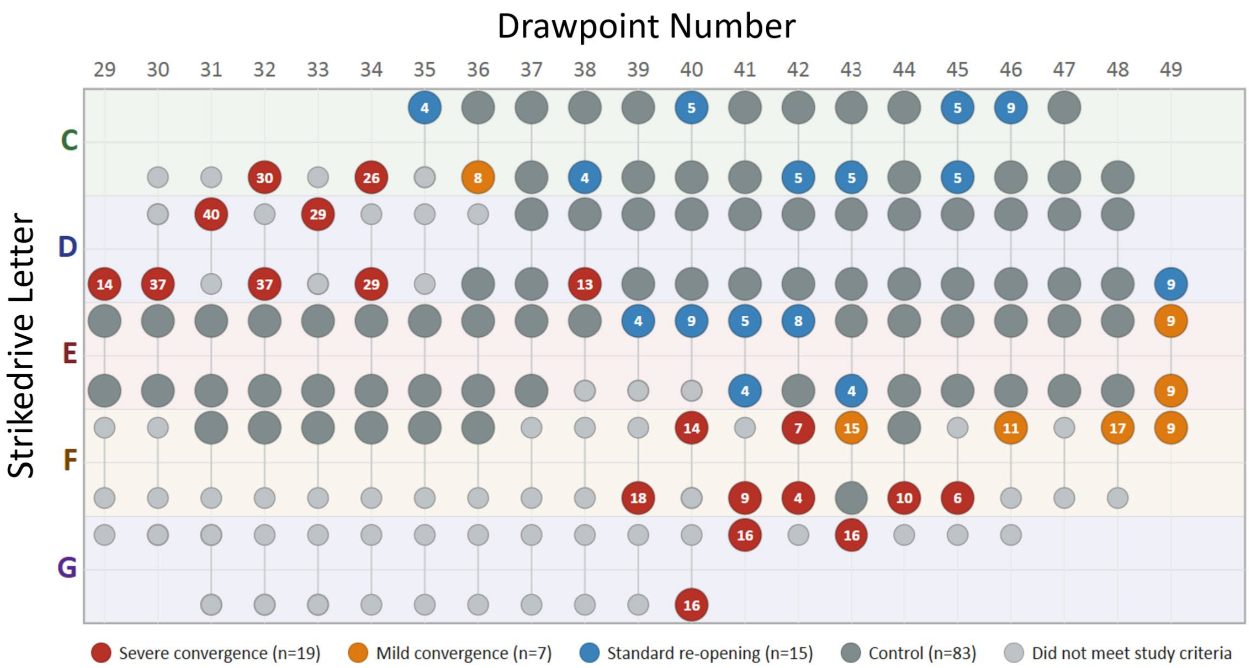


Figure 13 Plan view of the Lift 1 east cave extraction level showing the spatial distribution of drawpoint classification groups: severe convergence, mild convergence, standard re-opening, and control. The numbers in the circles are the months between closure and re-opening; n is the sample size. Drawpoints have north and south within each strikedrive, e.g. E29N and E29S

Grades for Au and Cu are reviewed using the actual grades within these 3 groups and compared to 2 PCBC models, the 2013 initial model run before mining began, and the 2022 post-reconciliation PCBC run. The 2022 model uses template mixing and various drawpoint drawcone shapes to capture column variations in lithology, fragmentation, and grade performance. The 3 groups (severe, mild, and standard) are also compared to a control group of drawpoints that never experienced any significant interrupted draw.

Severe convergence drawpoints (n=19) experienced significant production drift convergence resulting in collapse and extended closure and requiring redevelopment before production could resume. The convergence conditions at these drawpoints led to observable compaction of the draw column. Once production was re-established, the draw column geometry had changed significantly from the original drawbell blast design, forming a much narrower and localised area of draw (further explained in Section 4.3). These drawpoints form the primary subject of this analysis.

Mild convergence drawpoints (n=7) experienced measurable convergence and closure requiring the same re-opening detection criteria, but where the degree of collapse and compaction was observed to be less than the severe cases.

Standard re-openings (n=15) met the re-opening detection criteria but were not associated with convergence. These represent drawpoints that were closed at elevated HOD values and subsequently re-opened to support increased production targets.

Did not meet study criteria are drawpoints that fell below 50 kt, a 75 m maximum HOD, and 12 significant producing months above 600 t (a minimum monthly draw rate equivalent to approximately 2 loader buckets per day). A minimum HOD gain of 10 m between the closure and re-opening HOD was also required for any closure event to qualify. The majority of these drawpoints are in the F and G rows of the outer western part of the east cave footprint, where convergence caused collapse. A recovery level was established, however, production from that level falls outside the scope of this reconciliation and has not been considered.

Au and Cu grades within these 3 groups are compared against the 2013 initial PCBC model run prior to mining, along with the 2022 post-reconciliation PCBC run, and a control group of 83 drawpoints that never experienced significant interruption to production. All grade values are tonnes-weighted throughout.

Closure for the groups is defined when a drawpoint had 4 or more consecutive closed (zero production) months. Re-opening was defined as the first calendar month in which draw tonnes reached or exceeded 600 t, with a minimum of 3 post-re-open producing months. A minimum HOD gain of 10 m is also required.

Short-term grade performance windows take the drawpoints from each group (severe, mild, and standard) and review the 5 producing months before closure and the 5 months from re-establishment of draw at or above 600 t. For each window, the grade is weighted by actual draw tonnes. To compare the PCBC models fairly, the model grade is taken from the same HOD that was actually being mined during those months rather than calendar date. This is because the 2013 model was scheduled on a different timeline to actual production, so using the same calendar months would compare grades from the wrong part of the column.

Long-term grade performance is reviewed using the actual Au and Cu grade baselining from the re-establishment of draw HOD of each drawpoint. All production months post-reopen are assigned within 25 m relative HOD bins. For example, if a drawpoint collapses at 120 m HOD and then re-opened, it would be referenced to zero at the re-open H and start contributing to the 0 m+ HOD bin. Within each bin a tonnes-weighted grade is computed per-drawpoint for all drawpoints contributing to that bin, and the line plotted is the median of those per-drawpoint values. Bins with fewer than 5 contributing drawpoints are excluded from all plotted lines. The 2022 PCBC line uses actual draw tonnes and actual HOD for the same drawpoints within each group with the only difference producing a model grade, as the 2022 PCBC is a re-forecast grade model done to best effort reconcile against the actuals. The 2013 PCBC line is a bit more complex, it uses 2013 scheduled tonnes, 2013 scheduled HOD and 2013 grades for the same drawpoints within each group. However, to match the actual HOD properly a HOD-matched approach is taken so that for each drawpoint the 2013 model grade is extracted at the same HOD as actual post-re-open production (e.g. finds the 2013 scheduled months where the 2013 scheduled HOD is approximately 120 m, and takes the 2013 model grade there, weighted by actual tonnes), therefore reflecting the original mine plan as an independent baseline prior to mining.

The control group line in the long-term graph uses a HOD-matching method to align with the post-reopen HOD of each study group drawpoint (severe, mild, standard). All 83 control drawpoints contribute their tonnes-weighted grade into 25 m absolute HOD bins based on the actual HODs from the study group drawpoints, producing a control median grade at each bin. In other words, for each relative HOD position on the chart, the control grade is looked up at the HOD corresponding to each study group drawpoints re-open HOD, and the group control line is the median of those individual lookups. This ensures the control line reflects what undisturbed drawpoints delivered at the same absolute HOD as each study drawpoint operating post-reopen.

For example, this is how the long-term graph is viewed using 3 severe drawpoints re-opening at 100, 120 and 175 m HOD. The +0m bin represents the re-opening HOD and can be viewed as follows:

- Actual: tonnes-weighted grade for each drawpoint at their actual HOD (100, 120, and 175 m). Group line is the median of those 3 values.
- 2022 PCBC: same 3 drawpoints, same HODs (100, 120, and 175 m), 2022 model grade at the same HOD. Group line is the median of those 3 values.
- 2013 PCBC: same 3 drawpoints, 2013 scheduled months where the 2013 HOD is approximately 100, 120 and 175 m for each respective drawpoint. Group line is the median of those 3 values.
- Control: all 83 control drawpoints contribute grade into absolute HOD bins. The control median is looked up at the 100 m bin (for the 100 m drawpoint), the 125 m bin (for the 120 m drawpoint), and the 175 m bin (for the 175 m drawpoint). Group line is the median of those 3 bin medians.

All 4 lines are therefore drawn from the same absolute HOD for each individual drawpoint before the group median is taken.

4.2.2 Short-term grade performance

The short-term analysis compares actual grade in the 5 months after re-opening against the 5 months before closure and assesses how accurately each PCBC model tracked actual grade post-re-open relative to its pre-closure baseline (Table 6).

Table 6 Short-term grade performance actuals and personal computer block cave after re-opening

Short-term, post 5 months re-opening	Au median grade change (actual)	Cu median grade change (actual)	Au 2013 accuracy change (model)*	Cu 2013 accuracy change (model)*	Au 2022 accuracy change (model)*	Cu 2022 accuracy change (model)*
Severe convergence	34% worse	31% worse	42% worse	47% worse	51% worse	43% worse
Mild convergence	3% better	8% better	12% worse	10% better	19% worse	29% worse
Standard re-openings	8% worse	13% better	31% worse	12% worse	22% better	36% better

*Model accuracy change expressed in percentage points (pp), not a true % change, pp is representing the change in the difference between modelled and actual grade between pre-closure and post-re-open windows. For example, if the model over-predicted actual grade by 10% pre-closure and by 52% post-re-open, that is +42 pp worse.

Grade performance in the 5 months following re-opening is differentiated by convergence class. For Au, severe convergence drawpoints delivered lower grade post-re-open than pre-closure in 14 of 19 cases, with a median per-drawpoint grade reduction of 34%. Cu followed the same pattern with 13 of 19 drawpoints declining and a median reduction of 31%. Mild convergence showed no significant systematic deterioration for either metal; 4 of 7 drawpoints improved on Au with a median per-drawpoint change of +3%, and 4 of 7 improved on Cu with a median change of +8%. Standard re-openings showed grade improving at 6 of 13 drawpoints for Au (median -8%) and 7 of 13 for Cu (median +13%).

The 2013 PCBC model showed reasonable pre-closure accuracy across all groups. For severe convergence, model accuracy deteriorated by a median of 42 percentage points (pp) on Au and 47 percentage points on Cu after re-opening. This is expected, as the 2013 model was not calibrated to post-convergence draw column conditions. For mild convergence the 2013 PCBC improved by 10 pp for Cu and was 12 pp worse on Au.

The standard re-opening group shows a +31 pp deterioration in 2013 PCBC accuracy for Au and +12 pp for Cu. However standard re-openings occurred at comparatively late stages of the cave life at high actual HOD, where the 2013 PCBC predicted elevated grades that were not realised post-re-open, and this overestimate worsened after re-opening.

The 2022 PCBC model uses actual draw tonnes and actual HOD from the full production history, making it a reconciliation model. Using the actual draw history, it over-predicted post-re-open grade for severe convergence drawpoints by a median of 51 pp worse on Au and 43 pp worse on Cu relative to its own pre-closure accuracy. For mild convergence, the 2022 PCBC was 19 pp worse on Au and 29 pp worse on Cu, a moderate deterioration, but without the severity seen in the severe group. For standard re-openings the 2022 PCBC actually became more accurate post-re-open, improving by 22 pp on Au and 36 pp on Cu, indicating the block model grade-HOD relationship remained intact.

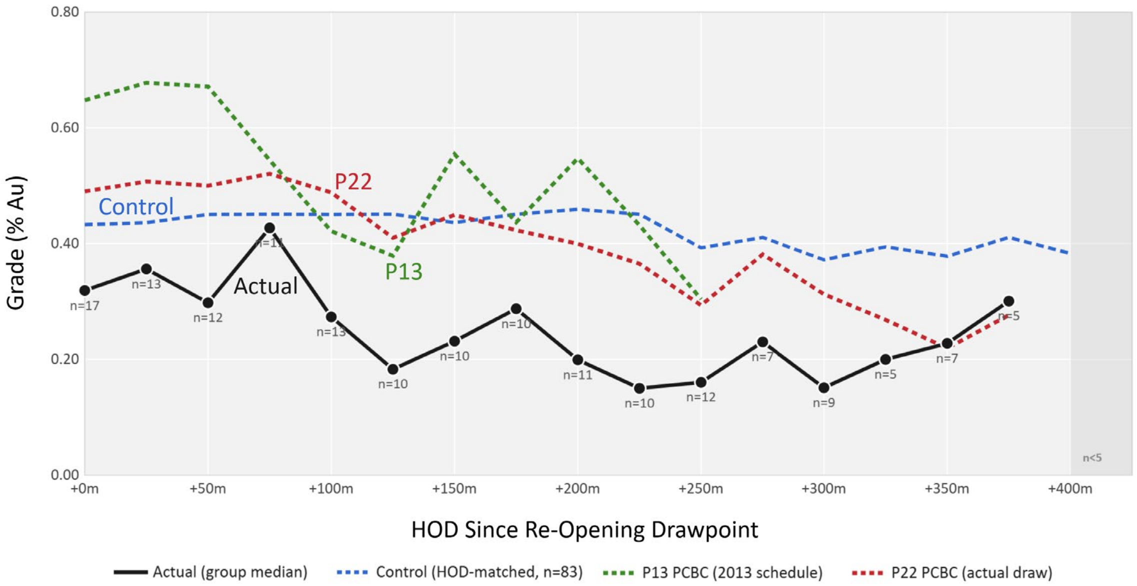
The actual grade data pre and post re-opening indicate that the severe convergence altered the fundamental grade-HOD relationship within the ore column while the mild and standard drawpoints remained relatively unchanged or improved. In addition, short-term forecasting and reconciliation models demonstrate that the ore column effects make it difficult to forecast grade, and that simply resuming draw after extensive convergence rehabilitation is not a continuation of pre-closure. The hypothesised mechanism is discussed in Section 4.3.

4.2.3 Long-term grade performance

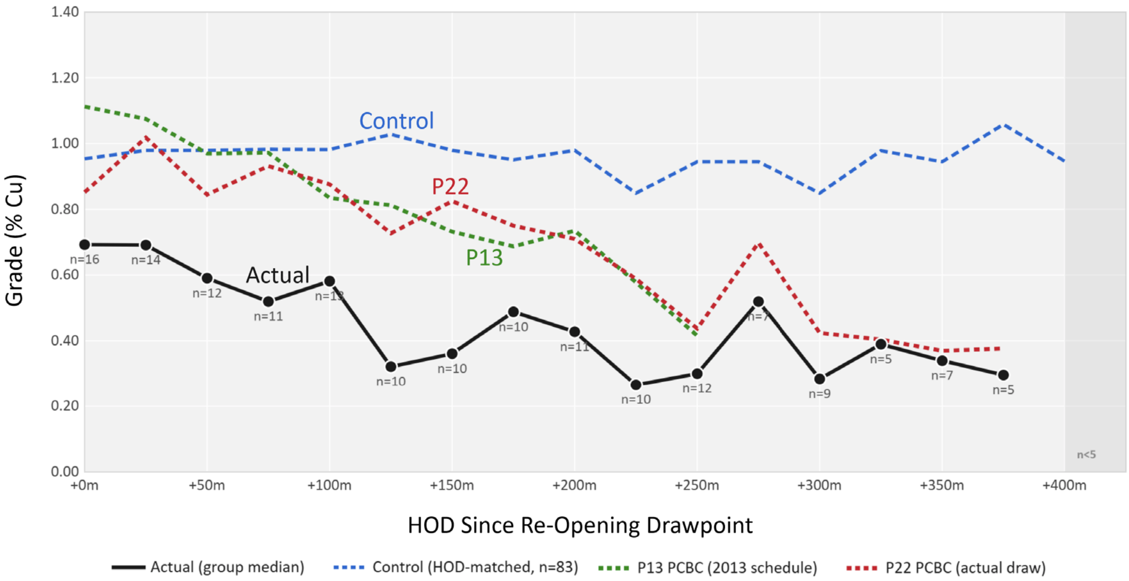
Grade trajectories were tracked over the full post-re-open production life of each drawpoint. HOD represents the vertical height of material drawn through each drawpoint from initial production and is used here as the primary measure of draw column advance. The dataset is capped to a sample size of 5 or more drawpoints ($n \geq 5$) to +375 m HOD for severe convergence drawpoints, +150 m for mild, and +75 m for standard re-openings. The severe convergence cases are reviewed as the primary subject.

For severe convergence, both Au and Cu grades are persistently lower than the control group and both PCBC models across most of the observable range (Figure 14). The control group remains relatively stable throughout the same HOD range, with less variability than the actual grades. Both PCBC models consistently over-predict actual grade across nearly all bins and both metals, with the 2013 model showing the largest over-prediction throughout and the 2022 model gap narrowing somewhat beyond +250 m HOD but remaining above actual across the entire observable range.

Longer closure times were associated with greater PCBC model over-prediction post-re-open on average, though the relationship is not consistent across all drawpoints and the sample sizes within each duration group are small.



(a)



(b)

Figure 14 Long-term (a) Au and (b) Cu actual grade trajectories by drawpoint group following re-opening. The x-axis is zeroed at each drawpoints re-open height-of-draw (HOD) to allow comparison across the group. Group medians of per-drawpoint tonnes-weighted grades placed into 25 m HOD bins (n≥5). Control is HOD-matched; 2013 PCBC uses scheduled HOD and grade, 2022 PCBC uses actual draw HOD and modelled grade

Individual drawpoint behaviour for the severe drawpoints is also noted to be highly variable in the early bins and becomes somewhat more consistent at higher HOD but remains at a lower grade than compared against the control group (Figure 15). The interquartile range (the spread between the 25th and 75th percentiles of individual drawpoint median grades at each bin) is widest in the first 200 m post re-opening, reflecting the high variability in re-establishment behaviour across the group, before narrowing as drawpoints trend toward a lower and more consistent grade level at higher HOD.

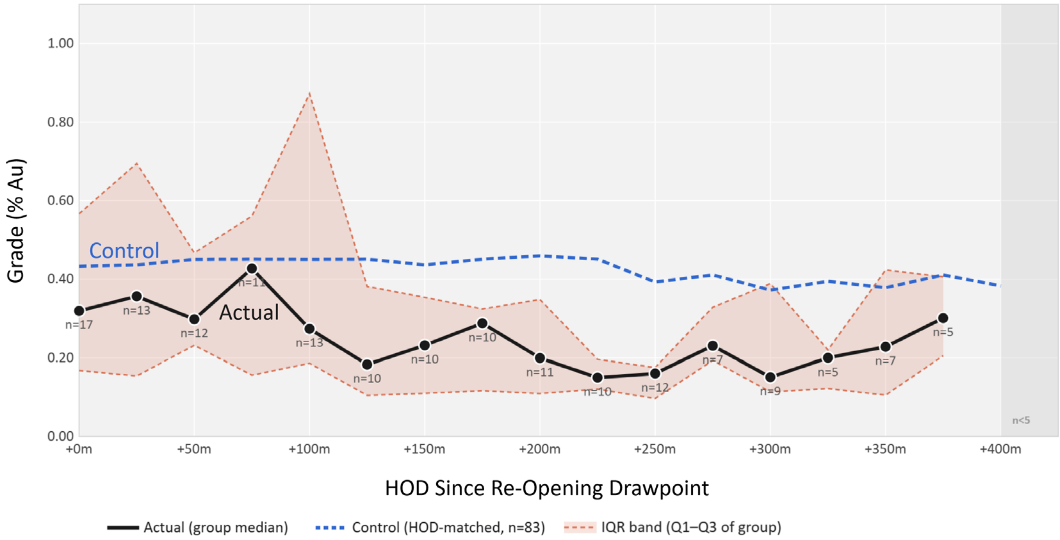


Figure 15 Long-term Au grade trajectory for severe convergence drawpoints. The line represents the group median at each 25 m HOD bin; the shaded band shows the interquartile range (25th to 75th percentile). The HOD-matched control is shown for reference (n≥5)

For mild convergence, actual Au and Cu grades start below both PCBC models at re-opening but increase with draw advance across the observable range. The 2013 model consistently over-predicts across the full observable range for both metals, while the 2022 model performs better. Across the +100 m observable range, the gap to the control group narrows with draw advance, in contrast to the severe group where the gap to control remains persistent throughout.

For standard re-openings, the observable range is limited to 3 bins. The 2013 model over-predicts for both metals across the available range. The 2022 model under-predicts Au across all 3 bins, while for Cu the pattern is mixed. While the results indicate that standard re-openings are not influenced in the same way as severe convergence, given the very limited range and small sample size, results should be treated as indicative only.

The long-term grade trajectories align with the findings of the short-term analysis. Severe convergence drawpoints show a sustained departure from expected grade-HOD performance that persists across the full +375 m of observable HOD. This indicates that the grade-HOD relationship within the ore column has been fundamentally altered and does not normalise with continued production. Mild and standard drawpoints show no comparable deterioration, with grade trajectories that generally follow expected cave depletion behaviour across their respective observable ranges. Both the 2013 and 2022 PCBC models over-predict actual grade for the severe group across the majority of the observable range, notably the 2022 model despite being calibrated to the actual draw history. The model likely fails to close this gap as it has not been adjusted to account for the complexities associated with re-opening drawpoints after severe convergence events. This outcome indicates that the effect of severe convergence on the ore column is not readily captured by rescheduling draw using the same drawcone assumptions as pre-closure, and that there are difficulties in projecting grade recovery following re-opening. The hypothesised mechanism driving this change is discussed in Section 4.3.

4.3 Observations within independent drawpoints and mechanism hypothesis

Distinct post-reopen grade behaviours are observed within the severe convergence group. The first is an immediate and sustained grade reduction from the point of re-opening, with actual grade falling well below the 2022 PCBC model throughout the observable HOD range (Figure 16). The second is a sharp grade ±spike immediately upon re-opening followed by rapid decline and persistent underperformance relative to both models (Figure 17), where the 2013 grade has been tonnes-matched as the pre-mining schedule was scheduled on a different timeline to actual production (done similar to the HOD-matching process previously discussed). However, in a smaller number of cases, post-spike grade aligns reasonably well with the 2022 model (Figure 18). Pre-closure grade behaviour across the severe convergence group shows some evidence of increasing variability in the months leading up to closure, though the signal is not consistent across all drawpoints. Together, these examples, along with the short-term and long-term findings and visual observations underground, represent the range of re-opening behaviours observed across the severe group and provide the basis for the mechanism hypothesis.

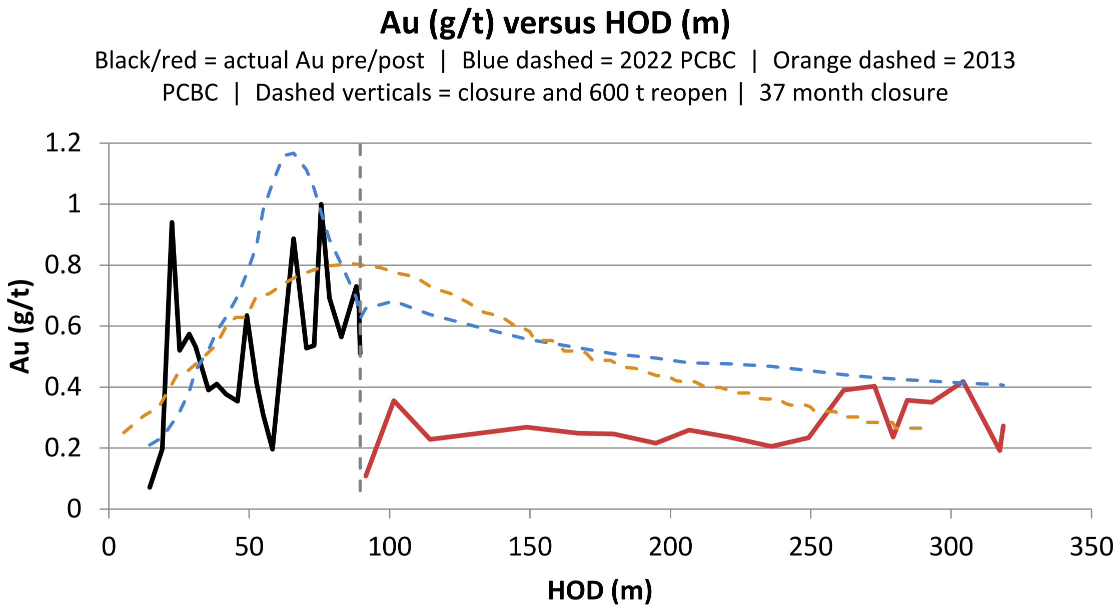


Figure 16 Grade versus height-of-draw (HOD) plot. Long-term Au grade trajectory example. Personal computer block cave (PCBC) models are generally trending well pre-closure, upon re-opening the grade drastically drops and maintains well below the 2013 and 2022 models

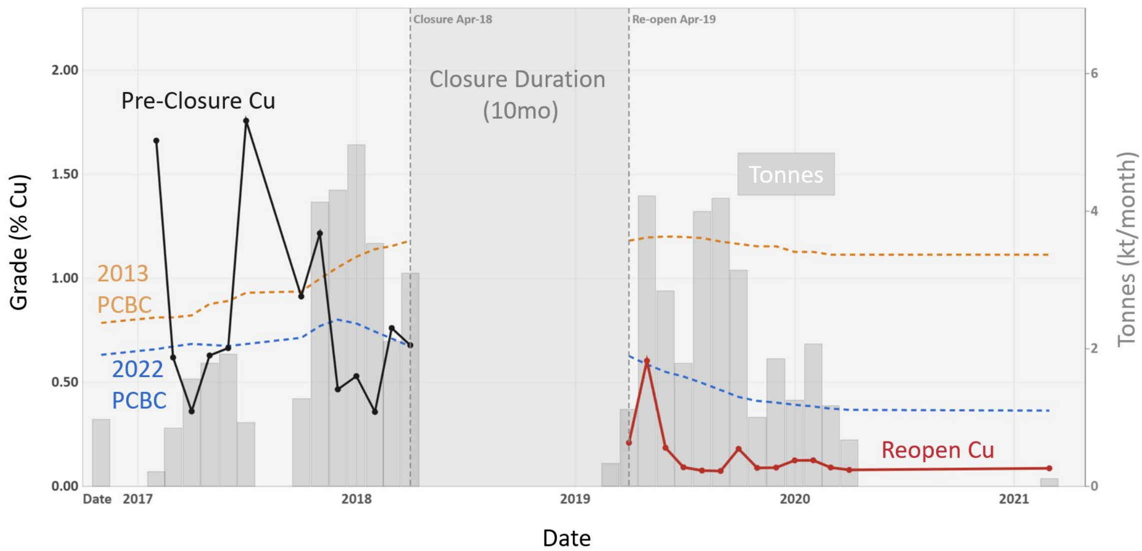


Figure 17 Grade versus time with tonnes plot. Long-term Cu grade trajectory example. Pre-closure shows intermittent mucking due to rehabilitation, production inconsistency and grade spikes. 2022 personal computer block cave model generally trending well towards pre-closure, upon re-opening the grade spikes, then drastically drops and maintains well below the 2013 and 2022 models

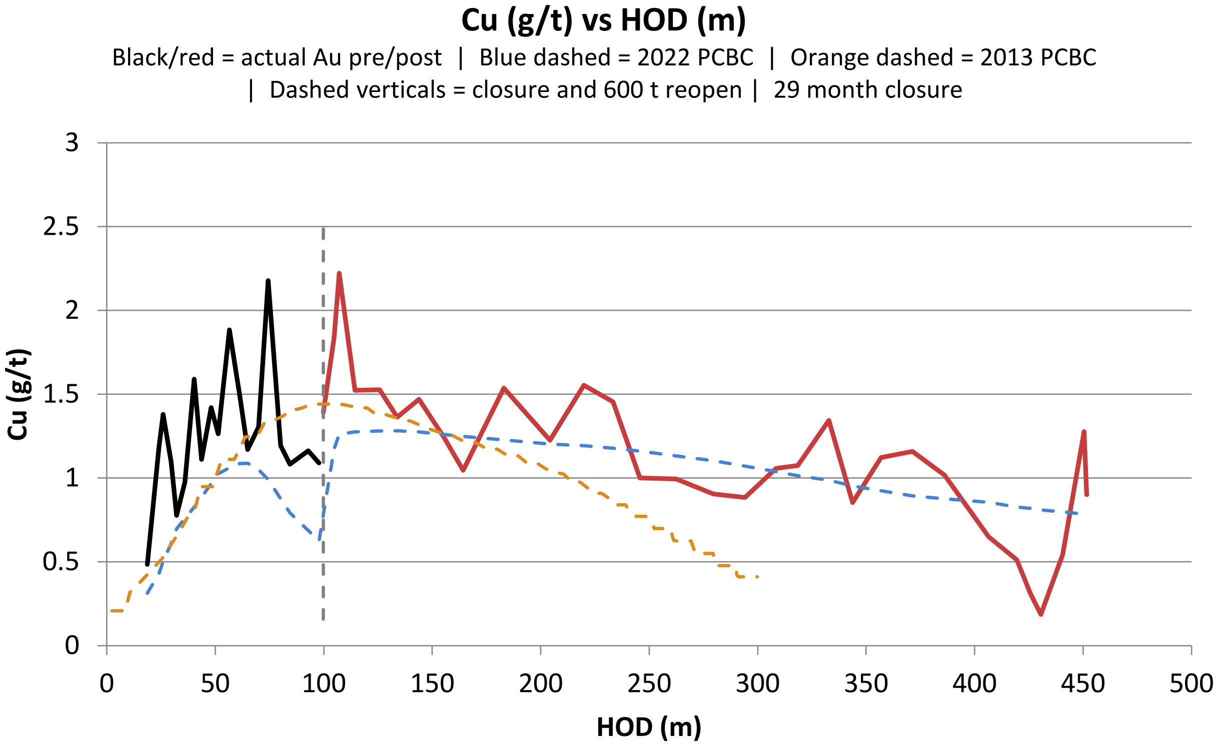


Figure 18 Grade versus height-of-draw (HOD) plot. Long-term Cu grade trajectory example. Personal computer block cave (PCBC) models are generally trending well pre-closure with a dip just before closure, upon re-opening the grade shows a positive spike and then continuously declines over time and maintains well with the 2022 model

The post-reopen grade performance following significant convergence events suggests a structural change within the ore column during and after closure, where the draw column fails to resume its pre-closure behaviour. While direct observation of the ore column is not always possible, the short-term and long-term grade data presented provide indirect evidence that the ore column is experiencing significant change.

A hypothesis has been developed to represent these notable post-re-open grade behaviours and field observations. As seen in Figure 19, illustrated is the hypothesised influence of draw effects due to convergence of the drawpoint. A progression of draw column behaviour is presented through 4 stages: normal interactive draw, high convergence with lateral convergence pressure compacting the ore column near the drawpoint, re-opening after collapse where draw within the highly compactable column eventually re-establishes, but through a much narrower isolated mobilised channel with no neighbouring drawpoint interaction.

As the draw column is narrowed, it is assumed production is then pulling tonnes and grade from somewhere else than pre-closure, likely higher up in the column. The post-re-open grades are also likely influenced by the checkerboarding pattern, as interaction would be poor due to the wide spacings compounded with the converged draw column. Once draw is maintained, a degree of progressive widening occurs as the compacted column walls erode to a state with continued production, possibly leading to interaction with neighbouring drawpoints or remaining at a narrow state, perhaps where Figure 15, suggests variability in grade reduces around an additional +200–250 m HOD. Field observations within the re-opening after collapse and re-establishing draw show a compacted drawpoint and ore column during re-excavation and then narrowing of the draw column when re-establishing draw, as seen in Figure 20.

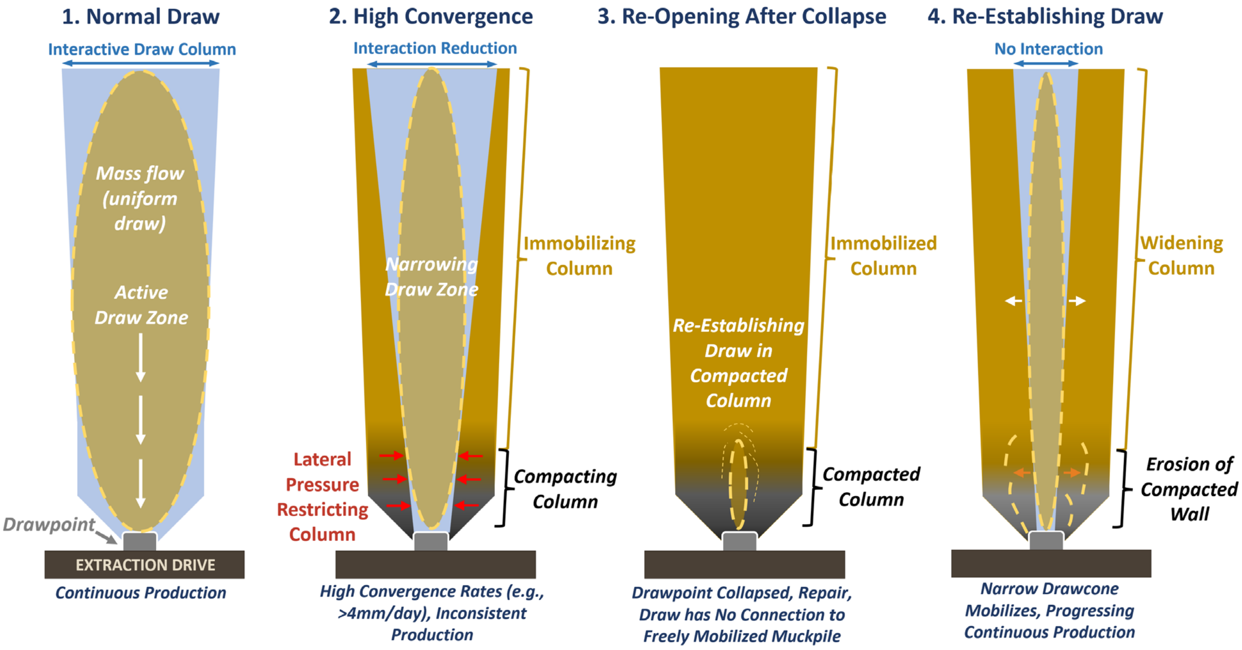


Figure 19 Hypothesised draw column behaviour sequence for a severe convergence drawpoint, progressing from normal interactive draw through column compaction near the drawpoint leading to closure, narrow channel re-establishment at re-opening, and gradual drawzone recovery with continued production

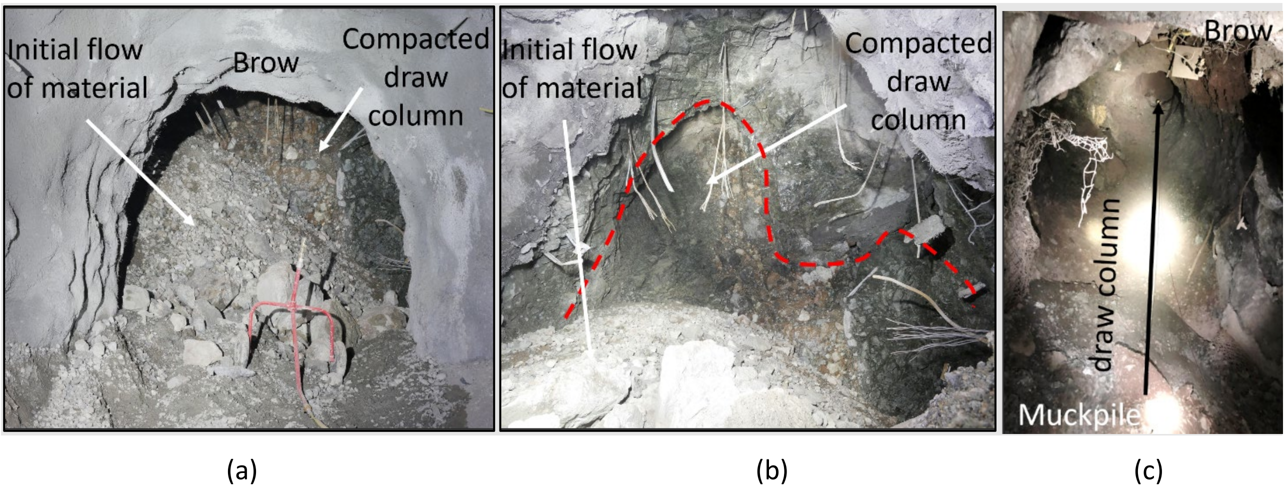


Figure 20 (a) Observed compaction at a repaired drawpoint beyond the brow, within the drawpoint, some material starting to flow on the left, water sprayer pictured; (b) View into the same drawpoint showing formation of a narrow draw column, red dashed line representing converged walls about 1 m apart; (c) ~0.7 m diameter draw column in a drawpoint within compacted material after draw has been established and is not flowing due to a hang-up

The F40N drawpoint at New Afton Lift 1 was previously presented for convergence rehabilitation in Kamp (2022). However, the grade data has been added and provides a field example of the hypothesised sequence, with geotechnical monitoring data, production records, and grade history available across all 4 stages (Figure 21). In general, the F40N was one of the better performing drawpoints post-re-open in the severe category; however, pre-closure Au grade decreases once convergence rates increase and mucking becomes difficult, then re-opens with a further reduced grade that declines over time as expected to depletion.

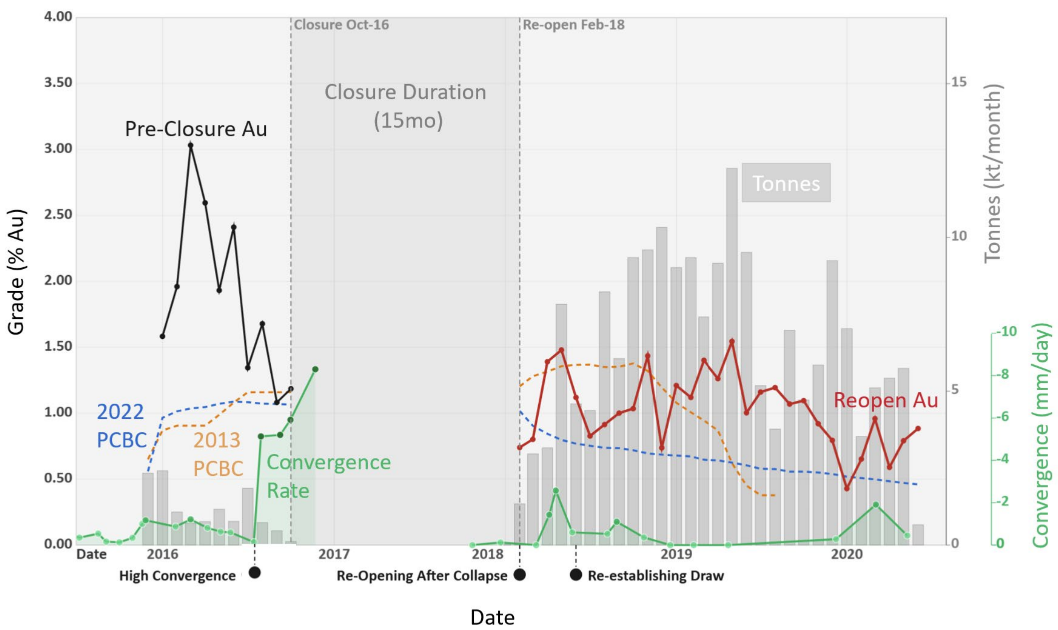
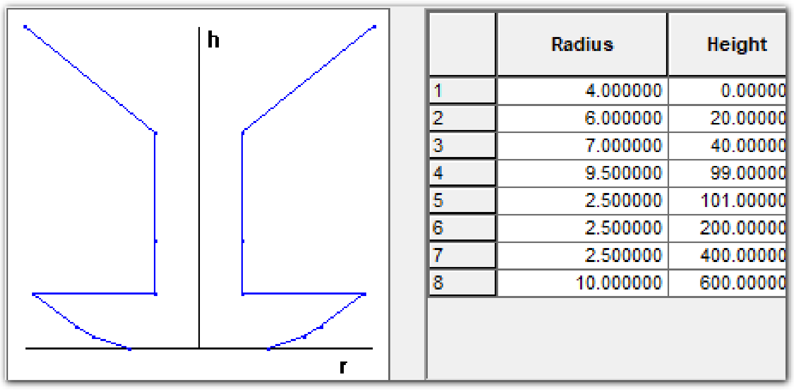


Figure 21 F40N Au grade, monthly tonnes and geotechnical convergence rate over the production life. Convergence rates through 2015–2016 lead to a 14-month closure, and the subsequent post-reopen grade response relative to the 2022 personal computer block cave (PCBC) model and 2013 tonnes-matched model. Note that the 2022 PCBC model uses a narrower cone for this specific drawpoint so it does not over-predict post re-opening

4.4 Testing the mechanism hypothesis in personal computer block cave

The objective was to test whether reducing the draw cone size for severe convergence drawpoints in PCBC can reproduce the reduced observed post-re-open grade. The hypothesis is that severe convergence creates a narrow, chimneyed draw column post-re-open, and the existing cone assumptions overestimate the draw column.

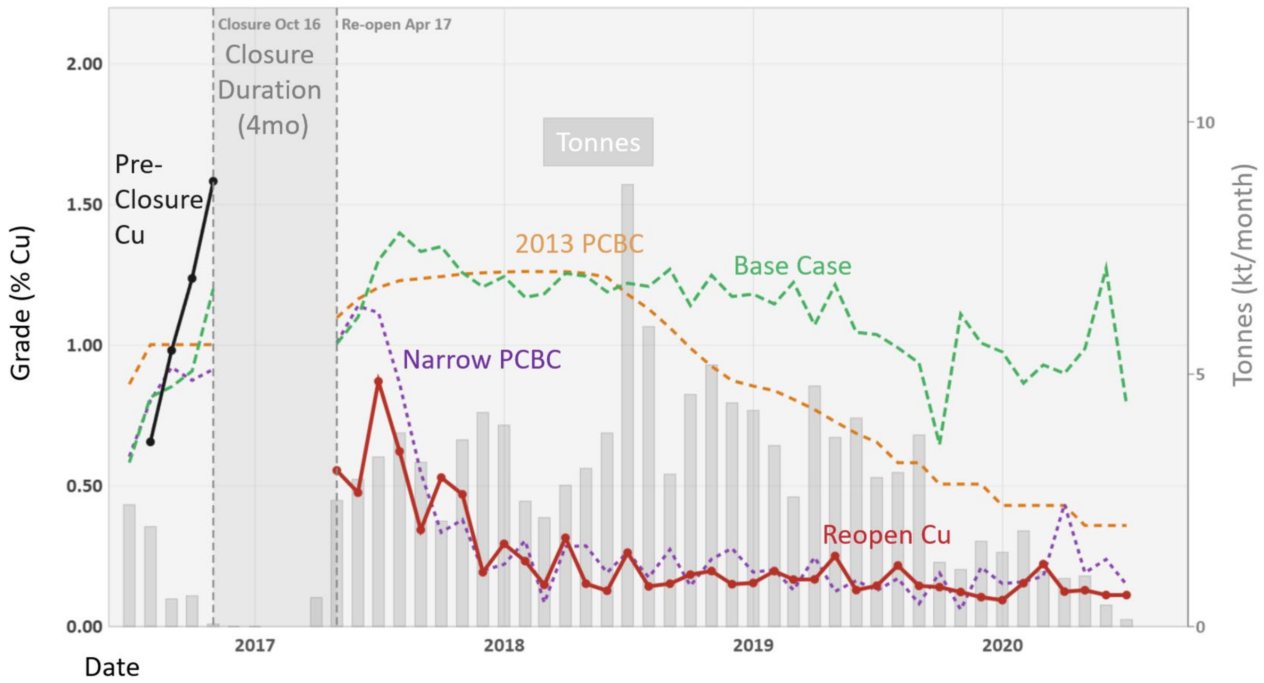
The model setup used marker mixing and has drawpoints set to a standard cone type as the base case, past tonnes were used to end of mine. Narrowed cone types were created for the severe group each based on the standard cone type but thinned to a minimum of 2.5 m radius above 50, 100 m (Figure 22), and 180 m HOD respectively. These HOD thresholds were derived from the HOD at closure for each severe drawpoint, representing the point at which the draw column became compacted and narrowed. Each severe drawpoint was assigned to the appropriate cone type based on its HOD at closure. Two model runs were compared. Model A used a base case with all standard cones rather than the 2022 reconciliation model, as the 2022 model had been calibrated with varying cone shapes and therefore does not provide an independent baseline. Model B was run using narrow cones only applied to the severe drawpoints.



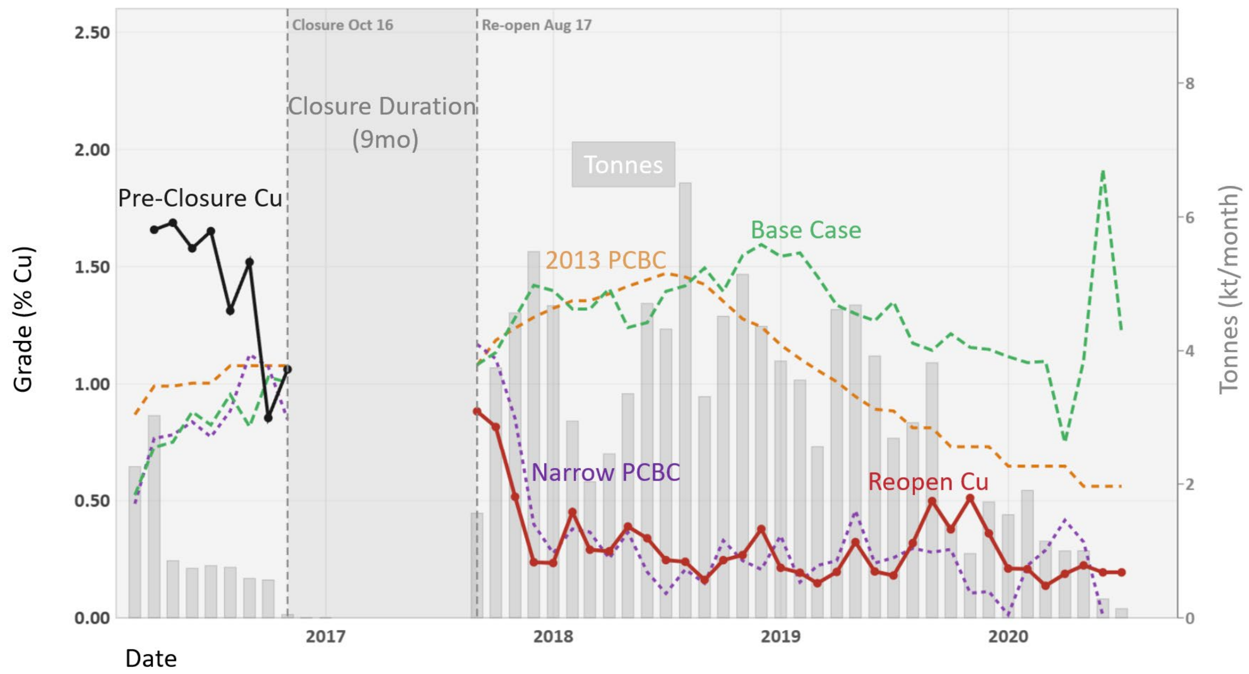
	Radius	Height
1	4.000000	0.00000
2	6.000000	20.00000
3	7.000000	40.00000
4	9.500000	99.00000
5	2.500000	101.00000
6	2.500000	200.00000
7	2.500000	400.00000
8	10.000000	600.00000

Figure 22 Example of narrowed draw column for the 100 m height-of-draw severe closure case (Diering 2026)

Across the group, the narrowed cone approach selectively reduced the divergence between modelled and actual grade relative to the standard cone, demonstrating that the HOD at closure is a physically meaningful threshold for defining the onset of draw column narrowing. Figure 23 illustrates examples of improved fit.



(a)



(b)

Figure 23 Long-term Cu grade trajectory with grade versus time with tonnes plot for selected severe drawpoints. (a) Drawpoint example 1 opened after 4 months and (b) drawpoint example 2 opened after 9 months. Re-opening shows declining grade from the base case model and 2013 model. Narrowing model provides a good fit to the grade data after re-open for both examples.

For the severe group, the PCBC sensitivity analysis produced grade predictions closer to actual post-reopen grades than the standard P22 PCBC for the majority of individual drawpoints assessed.

Where severe convergence has occurred and drawpoints are subsequently re-opened, adopting a narrowed drawcone is a more defensible reserve-modelling approach than applying the original pre-closure cone assumptions. This has practical implications for grade forecasting, production planning, and reserve evaluation at cave operations where convergence events form part of the production history. The current narrowed drawcone sensitivity run uses only a few grouped cone types based on broad HOD thresholds at closure, which represents a necessary simplification for an initial sensitivity study but does not capture the full variability in compaction severity across all individual drawpoints. Where the narrowed cone over-predicted or under-predicted actual post-reopen grades, the likely cause is that the assigned cone geometry did not closely match the actual degree of column narrowing at that specific drawpoint. A logical next step would be to assign a unique cone radius to each severe drawpoint, calibrated to best reproduce the observed post-re-open grade trajectory at that drawpoint. This per-drawpoint calibration would provide a more accurate picture of the range of draw column geometries that result from severe and mild convergence, and the resulting cone parameters could then be examined for patterns, such as whether cone radius correlates with convergence closure duration, or tonnes/HOD at depletion. The 2 examples presented in Figure 23 were selected to illustrate cases where the narrowed cone approach demonstrated improved agreement with actual post-re-open grades.

5 Conclusion

The performance of a block cave is governed by adherence to fundamental principles applied consistently in both space and time. These considerations cannot be treated independently. Production pressures and operational constraints frequently lead to deviations from these principles, and those deviations increase caving risk and reduce long-term recovery. Where production or operational target demands conflict with correct spatial and temporal sequencing, the consequences are not apparently immediate but tend to compound over the life of the cave in ways that are difficult and costly to reverse.

The operational examples presented from New Afton Mine illustrate the consequences of spatial and temporal decisions across several caving stages. Time-dependent undercut swell mucking schedules with defined tonnage windows were developed to prevent consolidation and maintain the necessary void for each undercut blast. For incomplete drawbell and undercut blasts and remnant pillars, recovery solutions were successfully applied using both undercut level and extraction level drilling approaches. Oversize management was shown to decline over the Lift 1 cave life while B3 showed no such trend, reinforcing the value of tracking and managing secondary breakage requirements over time. For mudrush, a practical basis for defining temporal equipment drawpoint exposure was provided. A draw control load shedding strategy targeting the highest convergence drawpoint and its immediate neighbours within defined HOD limits was proposed from operational experience to possibly manage active convergence. Where convergence exceeded the rate of rehabilitation, a checkerboarding re-opening sequence successfully recovered reserves from drawpoints that had been concrete-filled and closed. Re-opening production targets of approximately 200 tpd were established as a practical threshold for maintaining manageable convergence rates at previously collapsed drawpoints. In each case, the timing and location of the response proved as important as the solution itself.

At the whole level, Lift 1 reconciled exceptionally well against the 2013 PCBC, with actual contained Au within 0.1% and contained Cu within 0.8% of the pre-mining forecast, confirming that the mine plan was delivered as projected despite significant convergence and rehabilitation events affecting approximately 45% of the east cave footprint. However, this level-scale result masks considerable variability at the individual drawpoint level. A selective and detailed assessment of the grade performance of the Lift 1 east cave demonstrates that severe convergence events fundamentally alter the draw column geometry in a manner that persists well beyond the point of re-opening. To support this, a conceptual model was created to explain the data and visual underground observations. Severe convergence drawpoints delivered a median grade reduction of 34% on Au and 31% on Cu in the 5 months following re-opening relative to pre-closure performance. Both the 2013 and 2022 PCBC models consistently over-predicted actual grade for the severe group across the majority of the observable HOD range of +375 m post re-open, with the 2022 model improved but was unable to fully close this gap despite being calibrated using different draw cones and using the actual draw history. This outcome indicates that the grade-HOD relationship within a severely converged ore column is not readily captured by rescheduling draw using pre-closure drawcone assumptions. This mechanism was tested directly in PCBC by narrowing the draw cone for the severe convergence drawpoints, on the hypothesis that severe convergence produces a narrower, chimneyed draw column after re-opening. While additional work has been identified, across the severe group drawpoints, the narrowed modelled cones selectively reduced the divergence between the base case model and actual grade, in cases performing better than the 2022 model.

Mild convergence and standard re-opening drawpoints showed considerably less deterioration, with grade trajectories broadly consistent with expected cave depletion behaviour.

It is recommended that operations maintain adherence to caving principles throughout the mine life, with particular attention to the spatial and temporal sequencing of undercutting, drawbell blasting, and production draw. The examples presented in this paper demonstrate that deviations from these principles, even when operationally justified in the short-term, carry consequences that can persist across the full production life of affected drawpoints. Early intervention through draw control, load shedding of stresses, and timely rehabilitation when convergence is identified has been shown to produce significantly better outcomes than deferred response. For operations reporting reserves under public reporting codes, severe convergence and drawpoint re-opening events may require explicit consideration of whether the assumed drawcone geometry remains valid. Where re-opened drawpoints are materially represented in the remaining reserve, the basis for drawcone assumptions should be reviewed and, where necessary, disclosed or adjusted.

Appendix Literature review, categorising spatial and temporal caving principals with potential risks if not managed

Stage/description	Spatial practices	Temporal practices	Caving risk and operational complexities
Undercut blasting, swell mucking and location Starting point of the undercutting process and appropriate quantities and timeline for swell mucking	• Cave initiation point and advance direction are set by orebody (shape, grade, strength), stress field, infrastructure, structures and adjacent caved ground (Brown et al. 2022 citing Brown 2003) • Cave initiation shall start from existing caves and retreat away to facilitate cave initiation, reduce stress concentrations and potential rockburst risk (Cuello & Newcombe 2018) • Preferable to carry major faults normal to the undercut face rather than to approach them parallel. If possible, the cave front should not be advanced towards structures that could initiate massive wedge failures (Laubscher et al. 2017) • If the predicted hydraulic radius falls for completely within the stronger domain, the undercut should commence in the stronger domain and progress towards the weaker domains (Laubscher et al. 2017) • Direction perpendicular to an existing underlying or adjacent cave is more favorable to promote caving (Lolon et al., 2024) • Apex level retained in cave initiation zone to de-risk initiation, then partially removed as a trial for apex less High-W undercutting (Parsons et al.,2024) • Advanced undercut, minimal lead-lags, advance perpendicular to principal stress, and undercut before orepasses followed below to reduce induced stresses on the orepass (Stegman et al. 2022)	• Minimum 40% of blasted volume removed prior to the next blast to ensure enough porosity to absorb the expanding volume; remove up to 60% to inspect for pillars (Laubscher et al. 2017) • Grasberg block cave ramp-up, the mine achieved a peak undercutting rate of 10,300 m^2 per month. Planned to continue at rates averaging around 2,500 m^2 per month. Lead-lag typically 13 m on a 2.2 m ring spacing (Beard et al. 2024). • Minimum undercutting rate 9.6 m/tunnel/month, within 36 hours of blasting 20% should be drawn to confirm blast and back breaker holes, 10 buckets per week should be taken to minimize standing time, just before the next blast should be mucked, maximum sleeping time of UC rings is 90 days. (Parsons et al.,2024). • The rate of undercutting must match the rate of drawbell construction so that the undercutting front on the undercut level does not 'run away' from the drawbell development front on the extraction level. (Parsons et al. 2024) • The maximum distance that the undercut should lead the completed drawbell development on the extraction level below is dictated by the drawbell construction rate, to ensure that the drawbells can draw beneath the undercut area before the undercut material recompacts. Thus, the maximum allowable duration from the time an area is undercut to the time it is drawn from drawbells below should not exceed 3 months. (Parsons et al. 2024)	• Span interrupts (broken material over the minor apex has become compacted) point-load the extraction level, causing drawpoint or major apex collapse (Laubscher et al. 2017) • Remnant pillars from poor undercutting cause large extraction level collapses, especially where wider drawpoint spacing creates span interrupts; re-compaction or re-mining may be the only options. (Laubscher et al. 2017) • Drilling and blasting practices highlight the location of potential undercut remnant pillars (Laubscher 2000) • Long abutment residency, excessive lead-lags, long cave fronts, uneven draw, poorly formed apices, remnant pillars and incomplete drawbell firing all drive extraction level instability (Vanegas-Palacio et al. 2024) • Drawpoints closed by convergence: Palabora ~5% (incomplete undercutting, structures, uneven draw); Northparkes E48 L1 ~10% plus 6 of 10 extraction drives (post-undercut stress, long face, rapid propagation); Argyle ~40% (faulted weak rock, undercut-induced damage) (Stegman et al. 2018)

Undercut and cave front shape and rate Shape and rate of the advancing undercut and caving front	• Cave front advance orientation considers fixed infrastructure proximity (rail haulage, extraction level) and ground/stress conditions (Beard & Brannon 2018) • A concave face confines the rock mass behind the face, while a convex face allows relaxation. It is not good mining practice to mine from weak to strong rock. The rapid caving of the weaker rock might leave strong rock in the orebody boundary because the induced stresses are not high enough to induce caving. (Laubscher et al. 2017) • 'Big W' narrow incline undercut provides enhanced shaping of the major apex, promoting self-cleaning. Improved accessibility for inspecting ring blasts and identifying unsuccessful breakage (remnant pillars). Provision of a void for the toe area of undercut ring blasts, reducing the likelihood of choke blasting. (Batkhuu et al. 2024) • Max undercut front 250 m measured at right angles to the drill drives; veranda must not exceed 50 m (Campbell et al. 2020). • Undercutting front orientation shall not be parallel to the seismically dominant geological feature, nor to the in situ principal stress direction, to reduce potential rockburst risk and collapses. Undercutting front shall be less than 350 m to reduce stress concentrations over time (Cuello & Newcombe 2018) • Change in undercut heights targeted to have better results in terms of fragmentation, height of the undercut decreases, stresses tend to concentrate at the undercut front. (Hormazabal et al. 2018) • Face lengths >250 m not advisable; require 3D stress modelling of lag-induced stress increase (Laubscher et al. 2017) • Circular or square undercut shape will achieve a greater hydraulic radius for the equivalent plan area or square metres undercut than a rectangular shaped undercut. Also, a concave undercut face will have the stronger shape than a convex undercut face (Laubscher et al. 2017) • New Afton B3 design lead/lag 9.6 m, never breached >30 days; higher allowed only briefly during ramp-up at <50% HRcr (Parsons et al. 2024) • Carrapateena Big W use over crinkle undercut for larger apex pillar / higher life-of-mine pillar stability (Zhang & Hocking 2022).	• 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 5 months, are 7 m/month for PB2N and 11 m/month (Campbell et al. 2020) • Undercut rate shall be determined based on both the new area required to maintain the production rate and the seismic response of the rock mass (Cuello & Newcombe 2018) • A benchmarking average undercut rate of 2,085 m^2/month; at one operation where a rate of 5,000 m^2/month was achieved, a significant number of rock bursts were noted (Laubscher et al. 2017) • Undercut rate of undercut advance should be more than 10 m/month; rate of advance is a function of bell construction rate. At current bell construction rates of around 4 to 6 bells a month, the maximum length of the cave front (undercut length) ~ 250–300 m (Laubscher et al. 2017) • Undercut operational targets: 2,000–3,500 m^2/month, min advance 9.6 m/strikedrive/month, drawbells ~4/month average; face not stagnant >1 week (Parsons et al. 2024) • Benchmark: typical undercut rates vary from 500–5,000 m^2/month, with the mean in the range of 2,000 to 2,500 m^2/month (Pascoe, 2008, citing Brown 2007) • During early undercutting it is possible to briefly stop and start undercutting to sort out technical issues; once the undercut dimension nears 50% of HRcr, undercutting must be steady (van As & Guest 2020)	• >700 m undercut front parallel to major structures, led to fault activation with undercut and extraction level damage (Batkhuu et al. 2024). • Lead-lags play a prominent role in undercut rib pillar performance; where the maximum was exceeded by >200% at Grasberg PB2N, rib pillar bulking was most pronounced (Campbell et al. 2020, p.123). • Seismicity caused by unfavourable undercutting practices is one of the major caving challenges (Chitombo 2010). • Significant convergence in weak rock mass zones, up to 1.2 m wall closure at the brow of undercut drives, was recorded at Argyle during undercutting (Fernandez et al. 2010). • The rockburst potential is a function of high stress + brittle rock; rapid advance of the undercut (Laubscher et al. 2017). • • At Cadia East, major ground condition deterioration was experienced where lead-lags exceeded 40 m combined with high extraction ratios (Lett et al. 2016). • There is less seismic damage at the production level in the case of advanced undercutting compared to post-undercutting. However, more damage happened at the undercut level using advanced undercut than post-undercut. (Liu et al. 2022).

Stage/description	Spatial practices	Temporal practices	Caving risk and operational complexities
Drawbell blasting Drawbell blasting location and sequence Sequence and rate of drawbells blasted	• Oyu Tolgoi: drawpoint drives start 17 m behind UC face; full drawbell excavation ≥60° behind (Crook 2018) • Pillars from poor blasts or frozen ground can be identified mucking out the drawpoint swell (Laubscher et al. 2017) • Drawbells fire only behind the advanced UC; muck continuously until connection to UC is confirmed (Parsons, 2024) • Single shot drawbells are common in current caving operations	• GBC ramp-up: average drawbell blasting rate 8/month; peak 21 in September 2020. Kucing Liar plan: maximum drawbell opening rate 10/month (Beard et al. 2024) • GBC forecast: max drawbell opening 5/month per production block, ~12/month across all active blocks (Brannon et al. 2020) • Oyu Tolgoi Hugo North Lift 1: max combined opening rate 9 drawbells/month from 2 diverging undercut faces (Crook & Prince 2018) • For multi-fired drawbells, draw ≥60% of previous fire before the next ring (Laubscher et al. 2017) • DOZ ramp-up 2000–2006: average 3 drawbells/month; expansion 2007–2009 raised it to 5/month. Northparkes E26 Lift 2: 5 drawbells/month average (Aug 2003–Jul 2004); single-month peak 20 drawbells fired in July 2004 (not sustainable), Palabora Lift 1: overall 3 bells/month achieved. Rule of thumb: '3 drawbells/month is achievable, 4 is typical, 5 is good' (Ross 2008) • Henderson 7700 SW Panel: ~3 bells/month until late 2015, then accelerated to 12 bells/month to undercut the final third (Nov 2015–Jan 2016) (Shea et al. 2018) • Cave initiation phase, before critical hydraulic radius is achieved on undercut and extraction level: pull hard from drawpoints up to 50% of blasted rock swell from the undercut (Gonzalez-Carbonell et al. 2012)	• Larger veranda distances/durations create higher stresses wrapping around the undercut front, increasing risk of undercut drive damage, and increase the risk of re-compaction of the undercut blasted material, increasing risk of transmitting stress and resulting in extraction level drive damage (Crook 2018) • Once past the 45° rule, drawbell development must commence and complete as quickly as possible, especially in weak rock prone to re-compaction (Laubscher et al. 2017) • In kimberlite and porphyry rock prone to re-compaction when wet, the delay between undercut face and first drawbell commissioning must be minimized (Laubscher et al. 2017) • Drawbell construction rate is necessary to support the production rate and cave advance rate, if it cannot be maintained production targets suffer and the undercut will either reduce to match or will lead to excessive advance (deWolfe & Ross 2016)

Stage/description	Spatial practices	Temporal practices	Caving risk and operational complexities
Production mucking Drawpoint production location, volume and scenario based timing when to muck drawpoints Mucking (bogging) from the drawpoint	• Drawbells fire only after 45° angle between bell and undercut front (nominally 18 to 20 m), 35° minimum cave back angle; HOD-driven draw angle manages cave back geometry (Campbell et al. 2020). • DOZ wet muck spill severity: high-volume spills more likely under high draw rates and non-uniform draw; probability peaks when both draw rate and differential draw index are in their upper ranges (Ghadirianniari et al. 2022). • An isolated drawpoint develops a low-density mobile column above it; creating a preferred drawdown channel pulling dilution (Heslop 2010) • Northparkes E48: managing converging drives took precedence over even draw; increased bogging at and around converging drawpoints to shed cave load produced an uneven draw column; response was to re-prioritize call tonnage to lagging drawpoints and de-prioritize overdrawn ones (Snyman & Webster 2022). • Continuous mucking at and around an area of convergence can reduce convergence; After rehabilitation, a ramp-up mucking approach is taken with adjacent and nearby drawpoints supporting the re-established flow; if the rehabilitated drawpoint is not production-mucked, the area will likely experience high convergence again (Kamp 2022)	• Initial cave management: drawbell opening rate and cave back propagation are the primary constraints; lead-lags, undercut front length, draw/cave angle and draw rates are the dominant management criteria (Campbell 2020) • Cadia even draw KPIs (Cuello & Newcombe 2018 p.26) • Cave initiation/establishment is bounded by 3 rates: maximum draw rate (caving), drawbell opening sequence (establishment) and ramp-up rate. Draw rate shall be less than cave propagation rate to avoid excessive airgap and airblast risk. Even draw shall be the draw strategy to prevent isolated growth zones and avoid early dilution (Cuello & Newcombe 2018) • At Palabora, production draw rate was kept lower than the natural cave-progression rate; seismicity responded rapidly to changes in production rate, supporting the practice of pulling in alignment to the natural cave growth rate to minimize airgap (Glazer & Townsend2010) • Daily/shift call must be equally divided among available drawpoints; once the daily maximum is reached at a drawpoint, no further tonnes are taken; exceeding maximum calls drives isolated draw columns (Laubscher et al. 2017)	• DOZ ramp-up drove uneven draw, exacerbating wet muck spills and damage (Edgar 2020) • At Carrapateena the cave back stalled during propagation; the airgap drove active air blast risk management (Ormerod et al. 2024) • Argyle Mine 2012 to 2020: uncontrolled flow of material (UFM/mudrush) from cave breakthrough onward, tele-remote loading was required (Saepulloh et al. 2022) • Poor drawbell sequencing and low draw rates collapsed drawpoints and strikedrive at New Afton; rising convergence rates can expand to other extraction level areas as drawpoints become inconsistently mucked during rehabilitation (Kamp 2022) • Northparkes E48 dry-fines inrush (Snyman & Webster 2022). • Northparkes E26 Lift 1 fatal airblast, killing 4 mine employees (Vejrazka 2016) • The rate of draw must not be too fast so as to create a large airgap and which could lead to possible airblasts. On the other hand, if it is too slow, cave propagation will cease (Laubscher et al. 2017)

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