Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)
© 2026 Australian Centre for Geomechanics, Perth, ISBN 978-1-7636842-3-2
doi:10.36487/ACG_repo/2645_37

Managing change: geotechnical insights and learning from caving operations

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Abstract

Between the design and operational phases of a caving project, sites will typically experience variance from the plan resulting from geotechnical factors. During early construction and cave establishment, unexpected geotechnical conditions will be encountered; these may be due to a major geotechnical event, new geotechnical information or revised interpretation of design and performance criteria, each of which has the potential to impact the overall mine design and mining schedule. These variations and adaptations are disruptive, with an adverse effect on the efficiency of the operation. The changes are equally necessary to ensure personnel safety and optimal and sustainable extraction.

Learnings shared in this paper include examples of instances where geological knowledge was key to determining the root cause of the geotechnical event, combined with data from geotechnical monitoring systems to ensure suitable decision-making is undertaken to mitigate from events such as rockfall, variations to rock mass conditions and caveability of high-strength lithological domains in shallow low-stress environments requiring hydraulic fracturing processes.

This paper provides examples where geotechnically driven design changes were required to re-establish operations or recover from unforeseen geotechnical events. Examples from sublevel caving and block caving are discussed to demonstrate how limited early data can result in major consequences during cave establishment and conversely how, during production, a lack of knowledge can trigger major geotechnical instability that impacts safety and production of a caving operation.

Cases presented in this paper comprise groundwater characterisation and the operational impact for a sublevel cave operation from suboptimal planning for handling underground water ingress, operational practices associated with close-out of working ends between crew changes and the consequential impact on downstream ground stability, shortfalls in upfront analysis and the impact on airblast risk for a block caving operation, among others.

Keywords: *sublevel cave, block cave, early execution, geotechnical data, operational impact, investment*

1 Introduction

This paper provides a collection of learnings from cases where geotechnically driven design changes were required, during early execution of caving projects, to re-establish operations or recover from unforeseen geotechnical events. The case examples cover conditions from new cave construction through to establishing cave extensions and focuses on best practice strategies to manage unforeseen geotechnical outcomes.

In block caving, the orebody as a block is undercut using drill and blast methods that allow the orebody to fragment (Brown 2007). Undercutting involves drilling and blasting, and removing a layer of the broken rock immediately above an extraction level. This broken rock falls into a pre-constructed series of excavations

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called drawbells and access tunnels (extraction drives) where loaders collect the ore. The ore handling process commences in the extraction drives. When the undercut material above the extraction level is withdrawn, creating a cavern or void (the cave), this generates failure of the rock in the void (via stress or gravity) that falls into the cave. The progressive failure and collapse of the periphery rock drives continuous collapse, and the cycle continues. As the cave propagates vertically, the collapse of the crown and sidewall of the cave creates rock mass failure called subsidence, which is characterised as the formation of failure and often characterised by multiple mechanisms researched in detail in Sainsbury (2012).

Panel caving operates on the same principles as block caving, but in this variation of the method, the orebody or mining block is not undercut completely, but progressively developed as a mining front. Mining takes place in panels at some distance behind the undercut face. The cave front length is limited to less than 350 m in some cases to minimise overall stress concentration and deformation as it moves across the block or orebody at a constant angle to the direction of advance of the undercut. The advantage of panel caving is that it provides a continuous mining front and provides optionality with respect to future development expenditure.

Sublevel caving, as a variant of block caving, employs direct blasting methods to fragment the ore from a series of horizontally and vertically spaced access drives, or sublevels, that create drawpoint headings on a retreat cycle. Sublevels are separated by small, typically in the order of 20–25 m vertical intervals, and mining progresses downwards. An ore blanket is created between overlying caved waste material from the orebody host, and fragmented ore is drawn selectively at each retreating drawpoint (Brady & Brown 2006). Contrasting with block cave methods, direct ore fragmentation requires an increase in operational intensity but has better ore fragmentation control and grade selectivity than block cave operations.

2 Data collection and mine sequencing

The initial data collection phase of a caving operation provides the basis of inputs to mine design, sequencing and scheduling options of mine production required to ensure a robust mine plan (Read & Stacey 2009). Too often, data collection and analysis are neglected after mine development has been completed. Data collection must be treated as a priority to ongoing mine design and sequencing during the full project life cycle, similar to a design loop process, which can create a disconnect between actual mining responses being built into the future mine plan. This lack of integration typically leads to variations beyond the original feasibility studies, with negative outcomes with respect to operational productivity. This ongoing data review aspect should be built into an ongoing design loop for mine planning, where crucial data collection is maintained during all the phases of the project to ensure major risks and hazards are being monitored and mitigated. Table 1, constructed on experiential learnings, outlines the developing stages of a caving project with the anticipated major hazards. A generalised risk ranking is applied, and more emphasis should be placed on when the hazard is expected to present or diminish during the mine establishment schedule.

The long-term plan with robust trigger action response plans is required to assess risk and separate the early construction, cave establishment, cave propagation and steady-state production phases, where new geotechnical information or revised interpretation has the potential to impact the overall mine design and mining schedule.

Table 1 shows risks increase in line with deposit development and maturity and development stage. The existence of pre-existing workings has a significant effect on each of the hazards, onset of risk, and relationship to the execution schedule, which must be additionally accounted for. This paper presents these learnings.

Table 1 Caving hazards and onset of risks per mine execution phase for a greenfield block caving operation

Mine execution phase	Seismic hazard	Airblast	Mud rush	Subsidence	Collapse of workings	Comments
Early development	Nil	Nil	Nil	Nil	Nil	Acute conditions may lead to strainbursting
Cave establishment (undercutting and drawbell establishment)	Low	Nil	Nil	Nil	Nil	Acute conditions may lead to rockbursts
Construction (ore handling system, haulage shafts, crusher chambers)	Moderate	Nil	Nil	Nil	Nil	Changing stress conditions may cause rockbursts
Caving	Moderate to high	High	Moderate	Moderate	Low	Period of peak hazard with developing mud rush risk if dewatering is not maintained (overlying pits)
Steady-state production	Low to moderate	Nil to Low	Moderate to high	Moderate to high	Moderate to high	Most important period to maintain safe production Inrush hazard is maintained Ground deformation monitoring crucial to ensure ground support capacity is maintained to prevent collapses

2.1 Data collection and rigorous analysis

The early stage of development in a caving operation is crucial for collecting geological and geotechnical data that include rock mass characterisation, mapping and making rock mass observations using window mapping and scan line mapping methods. The focus on collecting sufficient rock mass information is essential to the entire caving footprint and the full caving block. An example provided includes a panel caving operation where limited rock mass information was available during studies to evaluate the caveability of the upper section of the cave column. This lack of data and analysis resulted in an intervention using hydraulic fracturing (Lowther et al. 2016) to mitigate a cave stall and airblast, causing a major downstream hiatus in the cave operation. The impact of the limited information is discussed in this paper, and the learnings are summarised.

The basis of the data collection program is to collect and characterise the rock mass conditions so that design decisions can be validated or reviewed. An example is provided to illustrate the collection of in situ rock mass data during mine development and comparison to data collected from drilling campaigns prior to initiating the undercut in a block cave. Scan line mapping data can be collected in a perpendicular and parallel direction to the drive and compared to previous mapping and drilling data. When scan line data were collected along the section of the undercut footprint, it was found that the core logging in the same location had overcalculated the fracture count per metre (FF/m) measurement. This resulted in an overprediction of the rock mass caveability and a review of the overall fragmentation. Figure 1 illustrates a robust scan line mapping program where the data were integrated into the design for fragmentation and hang-up frequency for drawbell designs.

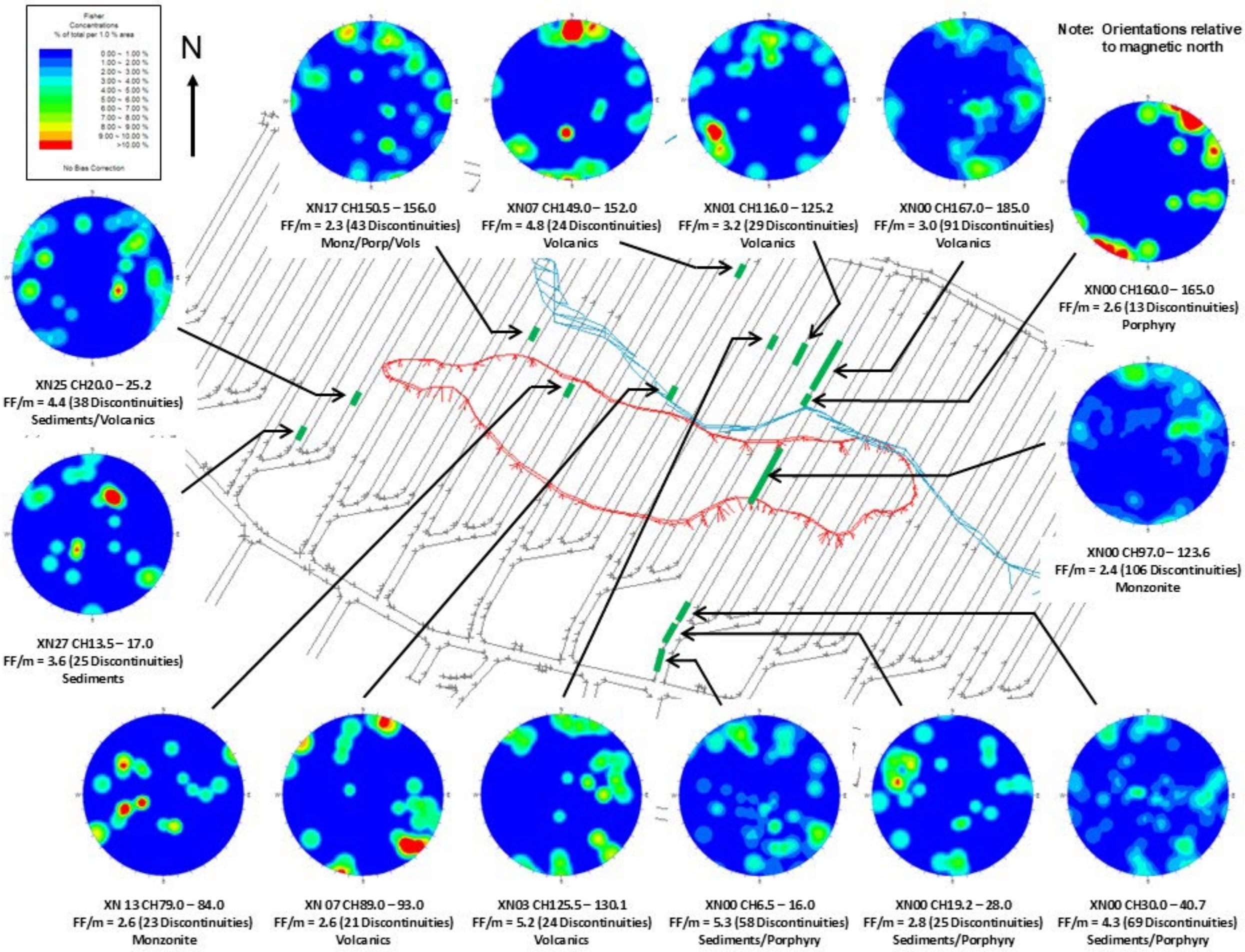

Figure 1 Undercut level scan line Fisher concentration stereograph data, fracture frequency and lithological domains

2.2 Structural geology and rock mass characterisation

Structural geology knowledge is equivalent to understanding the geotechnical behaviour of the mine prior to the commencement of production and is further explained in Lett 2022, where "robust structural geology and alteration models are available to provide insight to potential areas of elevated seismic hazard associated with lithological contacts (brittle rock mass such as volcanics and monzonite)".

Historically, multiple caving operations have incurred large delays attributed to the response of faults and intrusive contacts during cave establishment. Faults and intrusive contacts in these cases caused large, damaging seismic events and falls of ground that were later investigated and determined to be caused by unknown major geological structures.

In September 2009, a large damaging seismic event occurred at Ridgeway Deeps as the undercut passed under the eastern side of the sublevel cave (SLC) (Batkhuu et al. 2024), resulting in months of delay as the site increased the ground support, rescheduled the undercut sequence, and planned a custom draw strategy to recover the southeastern and northwestern areas of the orebody. An unknown fault that extended across the strike length of the footprint was discovered after the seismic event and was attributed to the pre-event deformation, with alignment to the moment tensor analysis during the post-event incident review.

Best practice for caving operations is to have a robust structural geology model and a geotechnical block model where integration of raw data, such as seismic data, can be overlain. A geotechnical block model will provide site personnel with an understanding of the range of rock mass conditions and ground conditions; the knowledge will be used to plan functional outcomes such as the undercut initiation position, undercut angle and caving angle based. Figures 2 and 3 from Lett (2009, 2013) illustrate examples from the same operation of industry-leading data collection and structural geology interpretation.

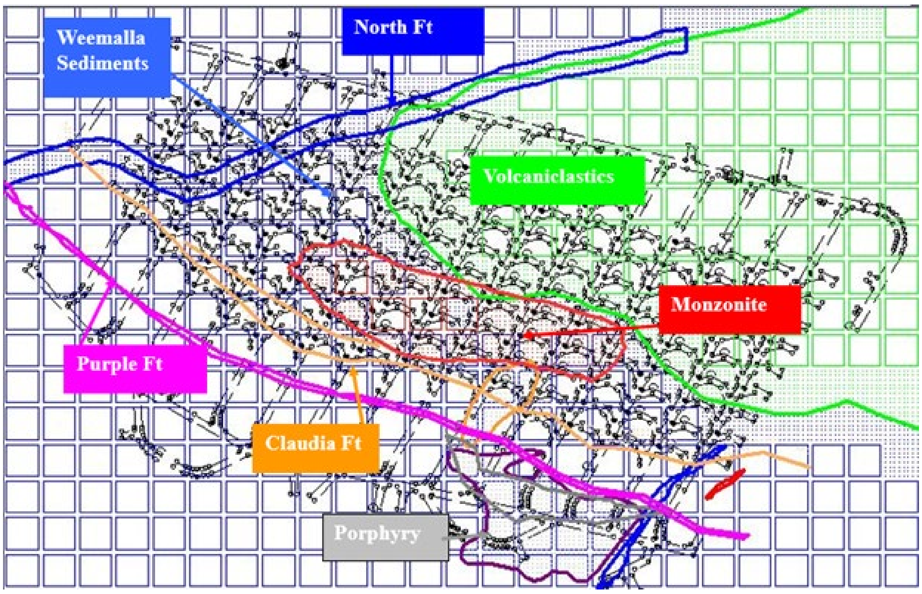

Figure 2 Lithological domains and major structures used as geotechnical domains

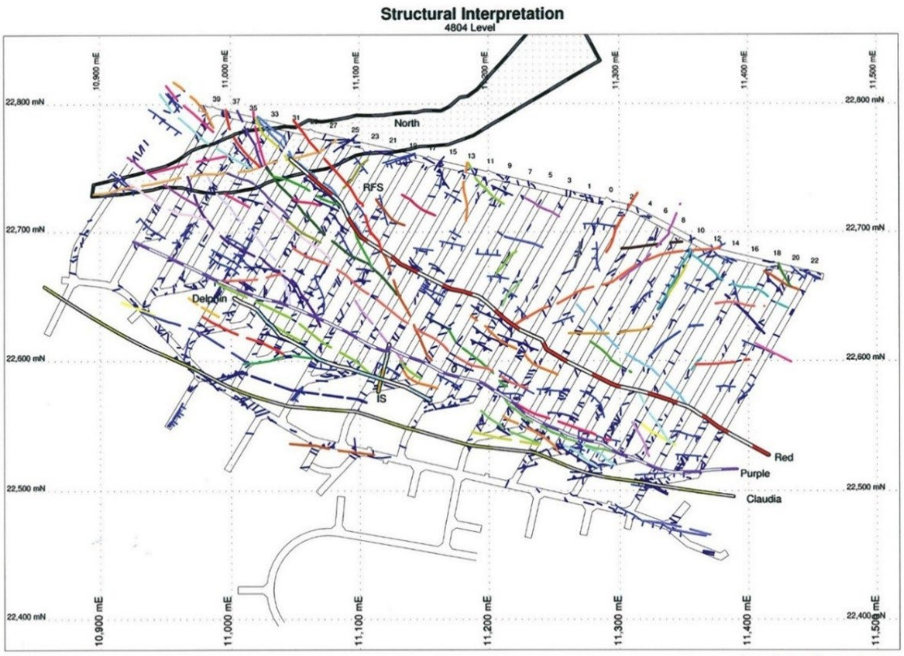

Figure 3 Undercut footprint with mapped structures

3 Operational learnings and case studies

3.1 Case study 1: advanced undercut block cave operation

During undercut initiation, a seismic event caused a failure of ground support, resulting in an 800 kg fall of ground; no personnel were injured (Figure 4). The local geology had not been identified as geological mapping had only been undertaken in the production levels, and was not deemed required for the heavy vehicle workshop area. This example identified the requirement to evaluate major hazards and the required inputs to be able to evaluate risks. In this instance, mapping of infrastructure areas is paramount to specify dynamic ground support requirements where exposure to personnel will be high due to utilisation of the workshop; rigorous characterisation was lacking in this particular incident. Post-incident investigation revealed that the workshop area had been evaluated as low risk for rockfall due to the distance from the stress abutment, and the lack of pre-existing structural information drove static ground support design with the expectation that seismic risk was low. The workshop area risk was re-evaluated as an outcome of the strainburst event, accounting for high personnel exposure and moderate seismic hazard. The workshop was situated 130 m from the stress abutment, intersected by porphyry dykes and bound by sediments, which caused the low-strength brittle rock mass to undergo strain. Post-construction re-support with dynamic ground support was installed before the workshop was recommissioned for use.

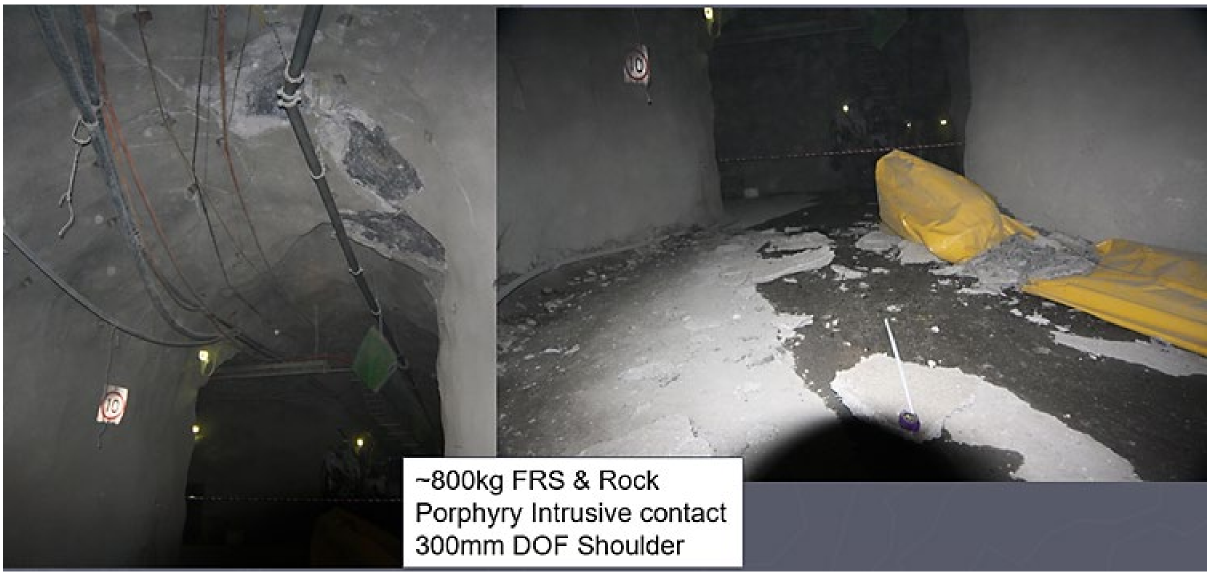

Figure 4 Photos of a strainburst event during undercut establishment phase

3.2 Case study 2: sublevel cave and block cave interaction

This example focuses on caveability, and the empirical methodology used to design a block cave (BC) footprint. Empirical caveability analysis for Ridgeway Deeps suggested that volcanic and sedimentary domains would both cave (Manca & Dunstan 2008) when the width of the extraction level was modified to 160 m in the volcanics and 120 m in the sedimentary unit. The operational challenge that later developed was how to ensure complete caving of the orebody despite a relatively short block height over a long footprint, called the aspect ratio. This is discussed in Lett & Capes (2012) where multiple cave shapes are described.

The BC production ramp-up was constrained by several scenarios due to the interaction between the overlying SLC and underlying BC:

- Potential seismic interaction and ground movement in the overlying SLC affected the underlying BC establishment.

- The number of working areas within the BC, and consequential BC establishment activities was constrained.
- Fragmentation size and ventilation were impacted.
- In addition, the initiation sequence involved an advanced undercut which requires the undercut and drawbell activities to be closely linked to mitigate the impacts of stress. The overlying pre-existing SLC operation created a stress regime that adversely affected the establishment of an advanced undercut.

Estimates made of the rock mass quality during the pre-feasibility and feasibility studies (Allman et al. 2007) highlighted that some of the rock mass domains were close to the design limits of caveability for the dimensions of the undercut. The east block was expected to have a slower cave propagation rate than the west block (Figure 5), leading to preferential flow from the western zone, and reducing or halting cave propagation in the east block. Early interaction between the BC and the SLC resulted in unplanned dilution to the BC ore column. This prompted the need to incorporate preconditioning into the mine plan as a way of de-risking the possibility of a cave stall or the cave being unable to recover the full economic reserve. A decision was made to trial preconditioning of the eastern volcanic domain in an attempt to reduce the rock mass quality and improve caveability.

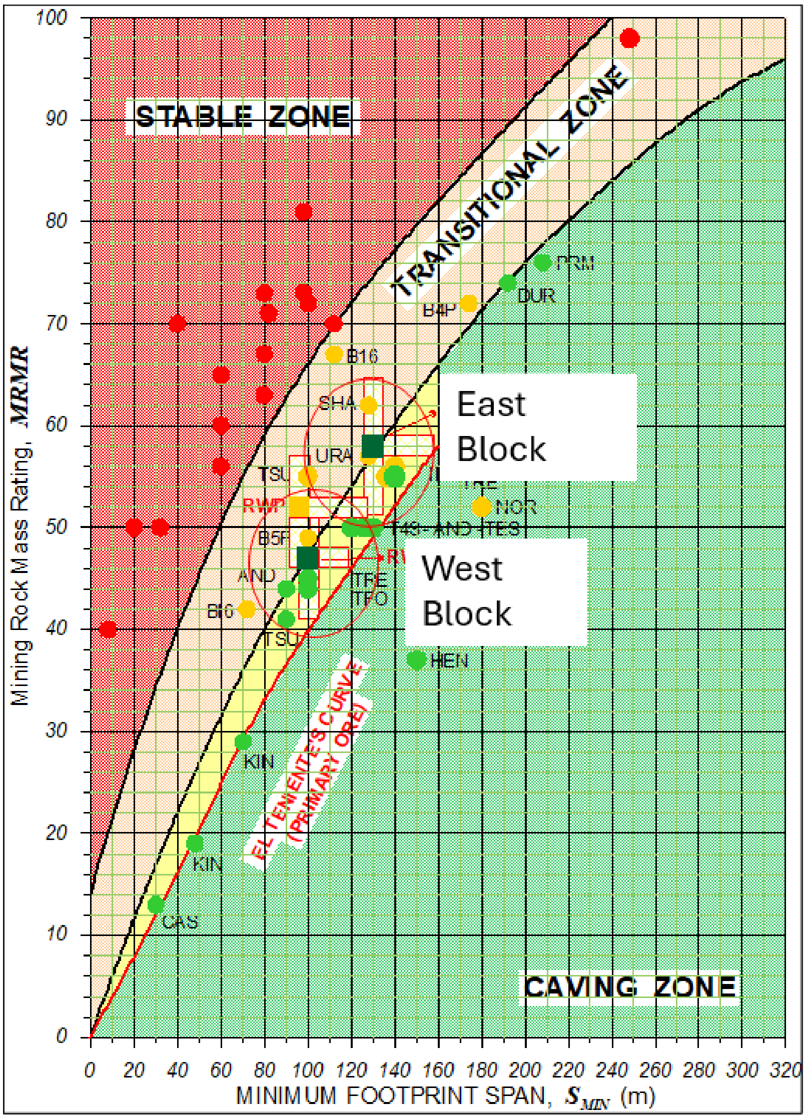

Figure 5 **Empirical caving chart (Laubscher 1994) illustrating the difference between the east and west blocks (Allman et al. 2007)**

3.3 Case study 3: post undercut block cave operation, caving to surface

This case study example discusses the impact of geotechnical domains having a greater impact on the cave than previously understood. The presence of two hard and highly competent separate geotechnical units was not incorporated into the Cadia East feasibility study cave behaviour analysis, and no suitable risk reduction measures were put in place to reduce the operational impact of cave stall or airblast. The risk reduction measures were possibly simple to plan, and the inclusion of a surface-based hydraulic fracturing program would have been a cheap investment relative to the potential outcomes of an airblast event (Lett et al. 2016a).

As a result of the inability to model the impact of preconditioning on cave propagation, a major gap was identified when the cave propagation slowed below the surface. The reduced cave propagation rate impacted the overall mine schedule and impacted the economic return because production was stopped for 6 months (Figure 6). The cave span narrowed and eventually stalled, and measures to implement a surface-based hydraulic fracturing program were initiated, which is explained in Lowther et al. (2016). When the draw was re-established, it was soon understood that the cave back failure was not connected to the cave draw, i.e. they were separate systems.

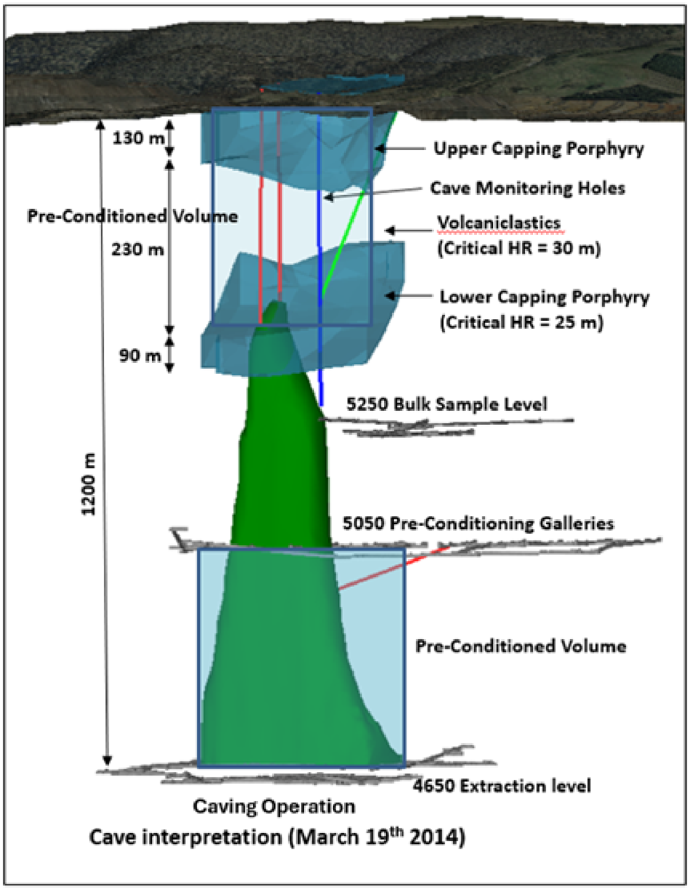

Figure 6 Cave position on 19 March 2014 showing the cave approaching the lower capping porphyry and cave stall position commencing (Lett et al. 2016a)

The events that impacted the cave propagation, and the role of a thrust fault and the capping porphyry units in stalling the cave, are summarised below:

- The location of a major structure called the thrust fault was structurally mapped (30 m-thick fault infill bound by blocky rock mass) in the sample drive during the pre-feasibility studies; the bulk sample level was used to undertake the hydraulic fracturing trial. However, the fault structure was not considered during the cave propagation modelling. This structure was to have a major impact on the cave propagation and would eventually cause the cave to stall, requiring new cave draw and drawbell scheduling, and triggered the need to mobilise a hydraulic fracturing program from surface, after Lowther et al. (2016) and Lett et al. (2016a).

- The cave response was as expected from the undercut to the preconditioning level, until the cave back span began to reduce to a hydraulic radius approximately equal to 12 m as it approached a sub-horizontal thrust fault where lower pre-mining in situ stresses had been measured and summarised by Lee & Lett 2012. This major structure was linked to the regional evolution of the orebody genesis and had a unique impact on the local stresses, and would unfavourably impact the caving response as illustrated in Figure 7.
- A further reduction in caving rate was observed using open cave monitoring holes and extensometers installed from surface that monitored cave propagation. Cave propagation slowed significantly throughout the upper geological sequence of porphyry units and is summarised in Lett et al. (2016b).

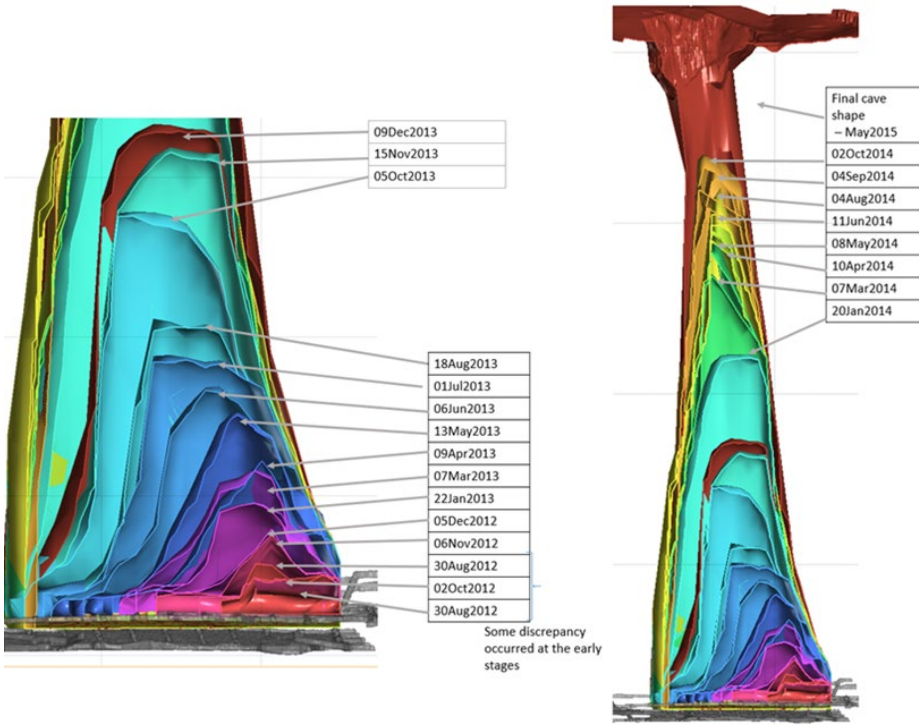

Figure 7 Cave propagation interpretations over time, illustrating a narrowing in span with cave height (Lett et al. 2016b)

3.4 Case study 4: post undercut block cave operation, caving below and adjacent to existing caves

Case study 4 references Cadia East Panel Cave 2 which was initiated at 1,600 m below surface and located east, adjacent to an existing cave in production with a footprint overlap of approximately 70–80 m. This overlap was termed the 'interaction zone' as both mining footprints overlapped in plan section over a block height of 270 m. The initiation point of the cave was directly in the centre of the footprint. This location was chosen to prevent early cave connection to the adjacent cave, which was still producing. Limited contingency during the studies phase was undertaken to evaluate the timing and impact on production impacts of the overlying footprint and how to manage seismogenic and physical cave interactions.

The influence of the existing cave on the footprint was underestimated at the time of cave initiation; however, it would become prevalent when caving of the deeper footprint started. The influence of the cave became understood as a zone of material that was slow to cave between the two caves meant that production from the footprint centre had to be slowed to focus on caving of the cave flanks. Caving simulations were complex to predict with numerical modelling, owing to the large nature of the caving block and the rock mass and stress effects.

The inter-cave dilation zone (pendant), defined as a zone of rock mass that has existed between the caves since their formation, was influenced by the rapid ascent of the cave apex, which resulted in focus switching to recovery of the material contained within this zone, further explained in Lett (2022). This focus led to significant effort being placed on the monitoring of the zone to determine the effectiveness of draw strategies.

Several design variables were recognised as influential in the formation of the pendant; they include but are not limited to:

- footprint vertical offset
- cave initiation point
- undercut span in north–south direction
- inconsistent preconditioning between caves.

Rapid cave growth was driven by implementing the hydraulic fracturing horizon. The implementation of draw strategies to facilitate growth and mobility in the western flank assisted in limiting further ascent of the apex. Figure 8 highlights the draw strategy focus, designed to generate cave growth, initiate the eastern flanks of the cave, and simultaneously limit growth in the cave apex. It was noted that draw strategies were primarily focused on managing airblast, and secondly on resource recovery.

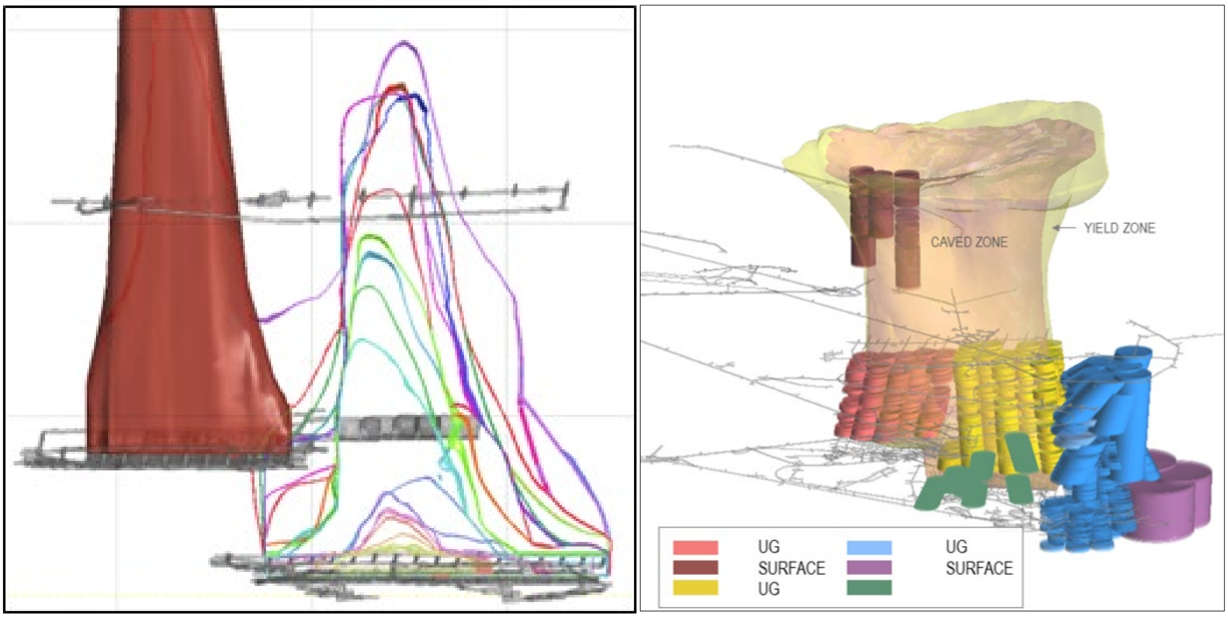

Figure 8 Cave growth, draw strategy and hydraulic fracturing programs designed to generate cave growth, after Lett (2022)

In summary, the cave propagated in the influence of the existing cave, and this had a large influence on the caving mechanisms experienced, where, through the draw strategy and hydraulic fracturing methods, a successful caving operation was established.

4 Cave interaction with overlying open pit operation

4.1 Case study 5: planning and execution of groundwater inflow risk management from open pit to underlying SLC connection

On cessation of open pit workings, and transition to underground SLC, groundwater inflow problems were experienced during the early ramp-up phase at an SLC operation in South Africa. As a function of orebody placement, the top three SLC levels, spaced 30 m apart vertically, were situated adjacent to the pit wall, approaching daylight within the pit shell, followed by the fourth level, developed within the immediate floor, some 15 m below the base of the open pit. Groundwater and rainwater inflow into the underground workings was therefore inevitable and expected. However, due to somewhat unpredictable locations of groundwater accumulation between the pit walls and the underground workings, together with short but intense seasonal rainfall events, preparation for effective water management in the underground workings presented an additional challenge.

A thorough groundwater characterisation program was developed and associated monitoring and water handling systems were implemented. The difficulties encountered, and resultant learnings, were ultimately attributable to shortcomings in preparation, in the form of appropriate investment into infrastructure and maintenance ahead of groundwater intersections and known rainfall occurrence. This, in turn, translated into frequent interruptions to the production cycle during the rainy season, and avoidable disruptions from water intersections at likely, but unexpected, water intersection locations.

It is important at this stage to make a distinction regarding the true meaning of ‘investment’. As shorthand for ‘finance’ or ‘money’, the investment cost of time and effort may be unintentionally trivialised. Given that time and effort are typically more demanding on those responsible for actual practice, and the reward of time and effort is ultimately only appreciated in the form of tangible output (revenue), the value of time and effort requires continual revisiting to maintain effective practice. The combined investment of funding, time and effort is collectively and equally required to achieve the optimal outcome, each of which is usually only ever secured through effective communication of their respective value and requirement for execution.

Consequently, it may be fair to say that the root cause for shortcomings experienced at the operation where management of groundwater inflow proved problematic could be inadequate communication – in this case, beginning with the originators, that is geotechnical owners, to the executors, and from face-front operators to management approval for the requisite budget approvals. The onus on geotechnical owners to maintain, drive and deliver this ongoing communication remains a perpetual responsibility, usually in the context of unwilling buyers, but cannot be neglected except at the peril of the operational success.

The images provided illustrate the gap between data awareness, i.e. consciousness of data requirements, contrasted with data value, i.e. attention to address data gaps, and transfer to execution. In Figure 9, the awareness of data required for in-pit groundwater monitoring for porewater pressure, and by inference saturation of the pit shell leading to ingress into the underground workings, is clearly evident in that instrumentation has been procured and installed. The gap between functional and non-functional instrumentation can be seen to be significant, in other words, ongoing investment into maintenance, and prioritisation of the value of the data have not been achieved.

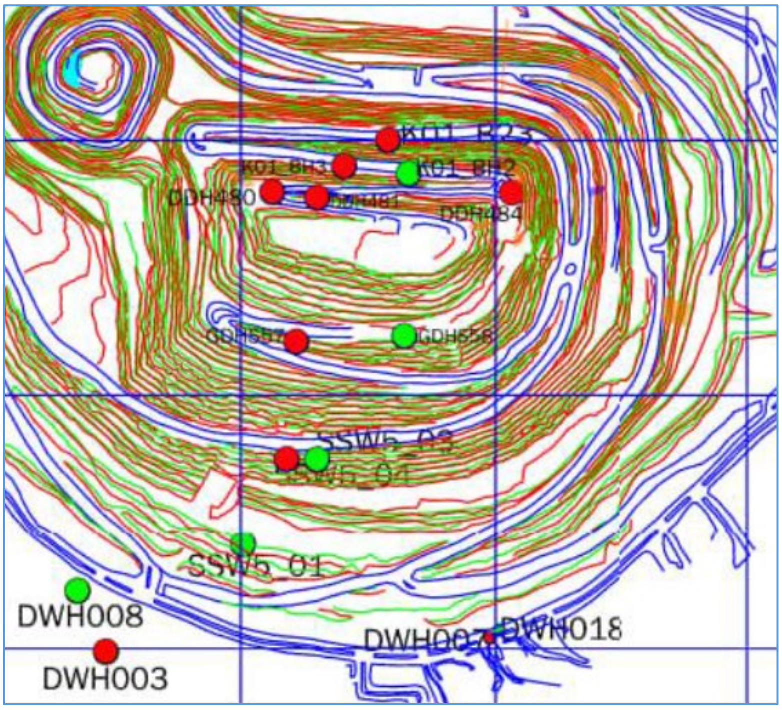

Figure 9 In-pit groundwater monitoring showing operational and non-operational piezometer locations

Figure 10 shows the program of sub-horizontal underground water intersection drilling that was commissioned and implemented for the operation, from which significant data were drawn to inform the location and volume of water intersections, particularly with respect to pit floor proximity, and orebody–waste contact. The program was successfully implemented, albeit at a late stage in the project after a significant volume of water that had not been fully anticipated was intersected during the development phase. In response, a water intersection dataset based on drillhole intersections was assembled and maintained, with some success in preparatory communication to production teams through establishing a water management forum. However, being reactionary, it was difficult to determine the knock-on effects of accommodating the water handling requirements as development practices already established had to be adapted.

In addition to the underground water intersection locations, seasonal rainfall resulting in drainage into the underground workings was limited to 2–3 months of the year. As a result, for 9 months of the year, rainfall ingress and water handling requirements were perceived as being largely redundant or temporary. The engineering and production cycle had to be interrupted to ensure pumping, piping, drainage and other associated water handling systems were kept in a state of maintenance in preparation for the rainfall season, and sporadic underground water intersections continued to present a challenge.

The cumulative cost of interruptions, road maintenance and rehabilitation due to water handling and groundwater ingress was not explicitly calculated, but could be estimated to contribute up to 5% of the cumulative annual production loss and ongoing maintenance costs for the operation.

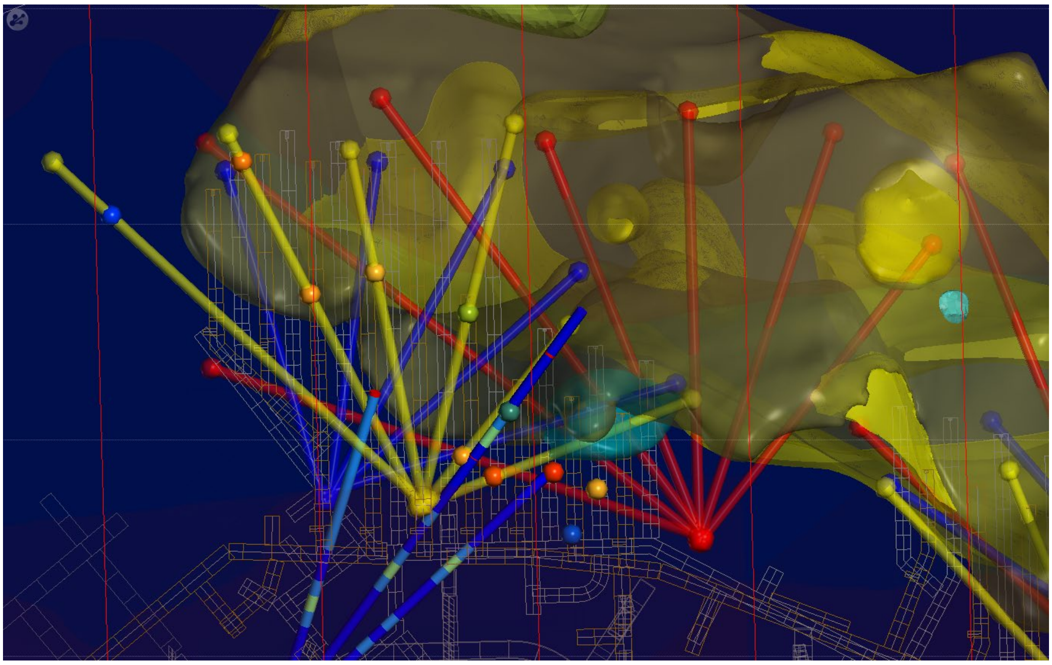

Figure 10 Underground water intersection drilling plan

5 Impact of operational execution cycles

5.1 Case study 6: integrating ongoing geotechnical characterisation, ground support and operational cycles

The impact of crew changes, combined with the underrepresentation of material lithological interface characteristics at the host rock–orebody contact, was experienced during the production ramp-up phase at an SLC operation. In this case, during the establishment of production sublevels, a routine crew changeover was effected on conclusion of waste rock development, at the orebody interface, following which the development end (SLC production access) would be temporarily halted, and resumed at a later time by a takeover crew to continue the orebody access drive development. At the interface between waste (host rock) and oredrive development, several contributing factors resulted in recurring rock mass failures and downstream operational consequences.

The change in rock mass character from waste (host rock) to orebody, in this case, was significant. A reduction in rock mass strength in the order of 50–100 MPa from waste to ore created a weak contact zone that affected some 5–10 m of lateral development across the contact. The rock strength reduction was further characterised by a change in rock type from metamorphic marble or gneiss to a variable competency kimberlite (orebody) intrusion. During the development of the waste access towards the orebody contact, up to 5 m or more of locational uncertainty contributed to unexpected intersections of the orebody sooner than anticipated. Measures to anticipate the orebody intersection typically consisted of sparsely spaced cover drill probing, and dependency on jumbo operators' sensitivity to drilling performance during face drilling.

As a result, ground support installation became routinely compromised. Due to unfavourable stability created by the orebody interface conditions, an intensified regimen of ground support was required, consisting of spiles or cable bolts together with the standard ground support of mesh, split sets and shotcrete. However, uncertainty in intercept location, together with the crew changeover, created a vacuum where the full complement of ground support installation was frequently delayed or compromised.

While several access drives remained forgiving and maintained a state of stability over the several months between crew change from host rock development to production crew development, several drives experienced significant ground falls at the orebody interface (Figure 11).

Ground falls occur at every operation and are therefore to be expected. Single, isolated occurrences create a short-term challenge to be remediated after which production resumes, with limited impact. However, the consequence of repeated occurrences was experienced at this operation, in that rehabilitation was no longer a once-off occurrence, but a pattern, with cumulative downstream impacts on production establishment and extraction efficiency.

Two key learnings are highlighted from this situation, both of which require investment where it is most needed and not where it is most desired. The first learning is the benefit of investment in ground probing, whether it be by increased density probe drilling (simplest, most direct and informative), or other less-invasive methods (geophysical sensing) to accurately anticipate the orebody contact location. Ground probing requires planning, budgeting and execution, and is frequently seen as a deterrent or interruption to the all-important objective of advancing development metres and is therefore resisted as a geotechnical priority. However, while a cover drillhole for each of the SLC access drives may seem excessive, the benefit of being able to anticipate within one blast round when the required increase in ground support needs to be installed is self-evident. This knowledge would enable upfront crew equipping and confident placement of the ground support.

The second learning is the relationship between the crews and the access drive development. Immediately following the second blast round through the contact, waste development would be transferred to oredrive development (production) crews. This transition would not necessarily be a seamless turnaround, i.e. development stubs would be left to stand for up to several months ahead of the production schedule, during which time completion of ground support for the last rounds was frequently overlooked as a close-out item due to crew rotation objectives. The foundational premise of expenditure (payment for metres), where it is needed rather than where it is desired, similarly applies in this case. The payment structure, enabled by the measuring process, recognised metres advanced without focused compliance with both loading and ground support completion.

While it is evident that practice in this case required significant escalation to improve the quality of execution, it is by no means unique. In short, a cut in upfront investment in geotechnical priorities, perceived as an unnecessary cost or waste of time (and therefore a ‘time and cost saving opportunity’) occurs broadly throughout the industry, with consequential operational impact. As geotechnical engineers, this situation is commonly known; the key objective, however, is to deliver this message to the ultimate executing levels, the teams who value rapid tonnage, but fail to recognise that sustained rapid tonnage can only be achieved when the preparation work has been fully accomplished. Using the analogy of masking tape in a painting project, the masking tape is discarded at the end and is deemed a disposable expense; however, painting without using masking tape makes for a messy task.

Figure 11 illustrates a case of severe chimney unravelling at the unsupported orebody–host rock contact. Several rehabilitation options were considered, including void fill and systematic sequential tendon and shotcrete support with bund walls to protect against further fall-out of rocks from the chimneying void. However, no satisfactory solution to re-establish the production stub was implemented, resulting instead in a workaround to extract the remaining ore from the level below. Downstream consequences of managing large blocks from the lower levels were therefore inevitable, or incurred a sterilised zone of the orebody with further hazard potential such as sudden caving and airblast affecting the lower-level drawpoints.

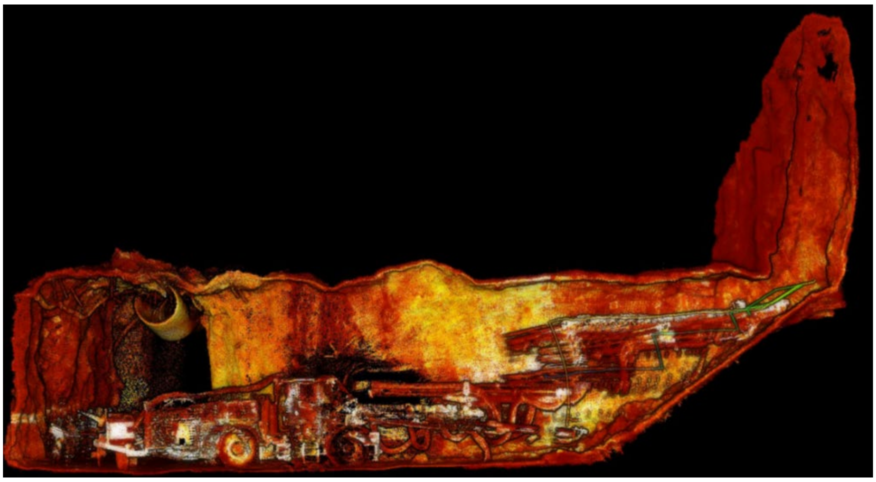

Figure 11 Chimney fall-out at the unsupported orebody–host rock contact

6 Conclusion

This paper provides a snapshot selection of several varied learnings experienced during the establishment of underground caving operations. The cases presented herein account for gaps in geotechnical knowledge, either through insufficient or incorrect characterisation, or the inability of numerical design and analysis to adequately anticipate challenges. Additionally, in addition to geotechnical knowledge, failures to implement appropriate engineering interventions for water ingress handling, which add to the risk of inrush, compromise safety and lead to operational disruption, are described. The integration between geotechnical requirements and operational targets is further added as a case study to illustrate where, beyond the geotechnical knowledge, engagement by the operational practitioners and investment owners is critical to achieve success within any mining operation, and in this case, cave operations.

The overwhelming message is that geotechnical integration, with thorough attention to accuracy, supported with meaningful investment in the form of finance, effort and time at all levels of the operational cycle, is essential to minimise the avoidable hazards encountered as illustrated in this paper. Errors and failures are not new to the business of cave mining, be it SLC or BC; furthermore, it is the continued successes that are achieved by which the industry is progressed. However, only by recognising the causes of failures, the reality of continued failures in spite of excellent advances in technical knowledge and technological solutions must be acknowledged.

In this way, the ongoing relevance of consistent and perpetual attention to ensure that the geotechnical requirements for operational success are met and adopted at all levels of the caving cycle, is kept current.

In summary, where geotechnically driven design changes were required to re-establish operations after unforeseen geotechnical events caused by limited early scope or study data, implications from various case examples included:

- Rock mass characterisation used to inform caveability across the full footprint and caving block.
- Cave initiation point selection to ensure full cave propagation and recovery of the orebody.
- Cave interaction is fully understood and evaluated with overlying mining levels, SLC or adjacent caves or open pit.
- Operational cycle management.

This paper provides examples of the development of hazards and risks experienced over the life cycle of a caving operation. Like the sea and nature’s forces, no matter how well advanced our tools, knowledge or experience, we can never afford to underestimate the potential for new and unexpected conditions, or for the same conditions to trip us up when we are not paying attention.

Acknowledgement

The authors acknowledge the colleagues and operational management from the respective cases who were available to provide their affirmation and support for the work represented in this publication.

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