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The challenges of transitioning to bulk underground mining

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ABSTRACT

A transition is underway in the copper business from open pit mining to bulk underground mining, principally caving, to extract resources too deep for surface mining. As a result, the challenges associated with deeper mining must be met, and the highly capital-intensive lengthy pre-production development period and subsequent "ramp up" to planned production levels must be carefully considered. Delays often occur due to a combination of ground conditions and construction complexity, increasing the time to reach planned production levels. This has financial implications due to the time value of capital or the reduction of cash flow at an established "brownfield" site. Insufficient attention is often given to the impacts of delays when considering a transition. Frequently, the reluctance to commit to Capex and start development sufficiently early is at the board level, often abetted by project teams, anxious to obtain funding approval, applying ambitious rates, and failing to communicate risk. Experience from cave development projects demonstrates that it is critical to appreciate the tyranny of schedule, especially at brownfield sites driven by high fixed costs. Most transition projects do not allow enough buffer time to account for the uncertainties associated with underground development and the subsequent production ramp-up. The challenges of transitioning underground are outlined, focusing on the time required for critical path development to ore, the construction of the ore-handling facilities, a reliable footprint, the production ramp-up, and then achieving targeted production rates, particularly during the "payback period".

1. INTRODUCTION

A transition is underway in the copper business from open pit mining to bulk underground mining, principally caving, to extract resources too deep for open pitting. As a result, the challenges associated with deeper mining must be met, and the highly capital-intensive, lengthy pre-production development to establish operations must be carefully considered.

Delays often occur due to ground conditions and construction complexity, increasing the time to the beginning of production. This has significant financial implications due to the time value of capital. Typically, project evaluation includes a cash contingency as a percentage of the project cost, but seldom a time contingency or even an overt assessment of what late delivery might mean to the business. Insufficient attention is given to the impacts of delays when considering the timing of a pit ramp-down and an underground ramp-up or the transition underground from one production lift to the next. Frequently, the reluctance to commit Capex sufficiently early is at the board level, often abetted by project teams, anxious to obtain funding approval, submitting first-quartile project schedules but failing to communicate risk.

Experience from cave development projects demonstrates that it is critical to appreciate the tyranny of schedule, especially "brownfield" sites driven by high fixed costs associated with existing infrastructure and the need to fill the mill. Though it is vital to minimise any production gap as operations transition underground, there is often a reluctance to start access development sufficiently early to ensure that the ore flow, ventilation, and service systems are in place, with adequate further time allocated for the production ramp-up. Most transition projects do not allow enough project buffer time to account for the uncertainties associated with underground development (substantially a linear process) and subsequent production ramp-up (substantially a learning process – far too often learning the hard way about the orebody, equipment, operations, etc.).

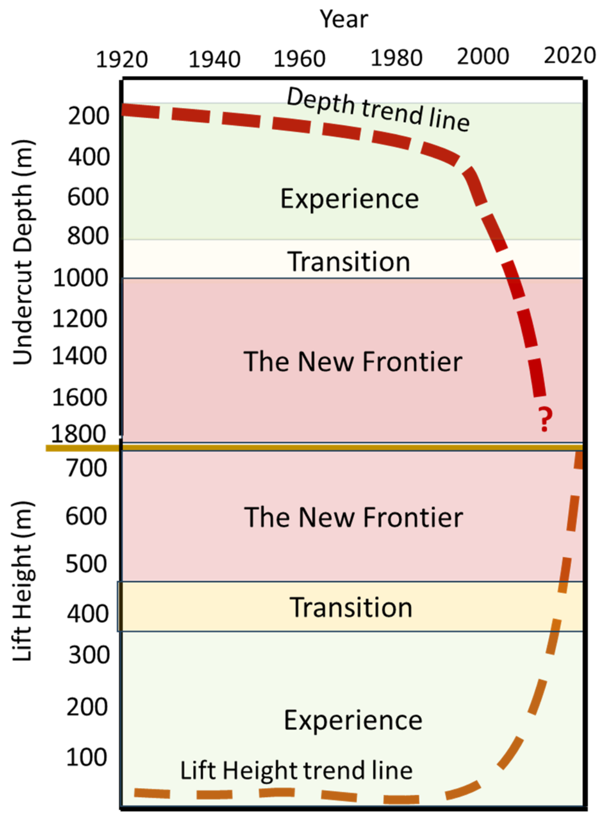

Figure 1 Lift heights and depth of the undercut level for selected caves.

The challenges of transition underground are outlined, focusing on the time required for pre-production critical path development to the first ore, the construction of the ore handling facilities, the production ramp-up and the setting of achievable production plans, particularly during the "payback period". The concepts of construction and production reliability, fragility and the recognition of excavations as key assets are discussed. Although significant efforts are made regarding resource evaluation, the quality of Orebody Knowledge, specifically with respect to anticipated ground conditions, required for good transition decision-making is too often limited.

2. TRANSITIONING

Copper mining has begun transitioning from large-scale open pits to caving operations to recover deeper ore as pitable reserves become exhausted. These transitions result in production footprints over 1000m below the pre-pit surface. This has implications, including higher stress, more pre-production development, a longer time to first ore, impacting value, and the risk of a production gap during the switch to underground. Decisions must be made at the correct time to ensure a smooth transition process.

Caving operations are moving deeper and operating higher lifts, as shown in Figure 1. The increasing depth of caving and the increasing lift height give rise to distinct challenges beyond prior experience. Previously accepted rules (often "of thumb") may no longer apply.

Though mining at depth is not new, for example, deep gold mining in South Africa and nickel mining in Canada, caving operations that have come into operation over the last 20 years or so produce substantially higher tonnages than has traditionally been the case in metal mining. For example, PT Freeport's DMLZ cave (25 to 27Mtpa) is 1300 to 1700 m deep, the GBC cave (35 to 37Mtpa) is 300 m below a 1200 m deep open pit, and Newmont's Cadia mine (30 to 33Mtpa) is some 1400 m below the surface.

Typically, there is pressure on the study team to produce a positive result. A negative outcome is often regarded as a team failure. The value of a study outcome should measure the success of the study, whether positive or negative. For various reasons, there is a drive to gain stakeholder approval, resulting in many projects not being "Central Estimates", benefits being assumed without the downside being recognised, and the challenge of asymmetry. The focus on NPV tends to drive a theoretical production schedule, often with a reluctance to factor in risk appropriately. The reality is that actual cave performance generally exposes the weakness in NPV-driven design. NPV should be an outcome of the design rather than the driver. Risk and change in risk must be communicated to senior management and the board (change management cannot be simply a site process). This is probably best done by assessing the possible impacts of the proposed change in value (e.g., a common denominator such as kg/ounces produced, cash flow, and NPV).

The significant time lag (often >10 years) between the decision to proceed and when revenue is generated can tempt senior management to be more concerned with the impact of the estimated project value on the immediate share price than the realities of the project, on the basis that they will have probably "moved on" before objectives need to be met**.** At depth, excavations become more vulnerable to mining-induced stress and deformation changes that affect the load and displacement demands on the pillars and support. In rockburst-prone mines, dynamic loading of the rock near an excavation also adds an energy component. The result of these increased demands is that the production system is more fragile, with a higher potential for safety risks and a higher potential for mine construction and production delays due to damage and rehabilitation, unless the excavations are well-designed, constructed, and well-maintained during their operating life. Therefore, a robust design must consider constructability, particularly the schedule, the excavation's functionality, personnel exposure, the long-term behaviour of the rock mass containing the excavations, the required (support) maintenance schedules, and the financial impact of all these factors.

Increased lift heights with production footprints in more massive brittle rock masses typically expose operations to hazards that must be managed to ensure an acceptable risk profile. This vulnerability must be managed to ensure a safe working environment, reduce production interruptions, and maintain asset operability.

A common hazard is damage to the production footprint. This can occur in the abutment zone, where construction is undertaken, and in the extraction zone during production. Because caving is a relatively inflexible method, there is limited opportunity to correct an inappropriate design. Having productive and available drawpoints, combined with a robust Material Handling System (MHS), is a more significant value driver than more traditional design approaches, which tend to focus footprint design on draw interaction and recovery. Therefore, there is a strong incentive to design, construct, and operate a reliable, holistic production system. This, in turn, leads to safer and less risky operations.

Appreciating the tyranny of schedule on a high-fixed-cost "brownfield" site is vital as it strongly influences project targets and metal schedules. However, the realities of traversing unknown ground conditions along the Critical Path development typically compromise the schedule. Most transition projects do not allow sufficient time to account for uncertainties associated with underground development (a linear process) and the subsequent production ramp-up.

A key is recognising that excavations, whether on the footprint or infrastructure, represent a significant investment and are the critical assets of the operation.

In a caving operation (as in any underground mine), there are two broad types of excavation: those that are part of the mine infrastructure and those that are directly part of the production process. Excavations for mine infrastructure typically need to function for the life of the mine, while production excavations have shorter lives consumed by the production itself. However, this difference is somewhat reduced with the advent of deep high-lift caves (lift heights >500m) and macro-block layouts.

Several burning platforms exist:

Mining at depth**:** Are we ready for large-scale underground mining at depth, with increased ground control and seismic hazards that require close attention to cave management and support requirements?

Time to build: It can take 10 to 15 years to develop and ramp up a large cave, with approximately 60% of the overall schedule associated with driving tunnels.

Production (revenue) reliability: Production forecasts must be reliable, a function of equipment, infrastructure, and often-forgotten footprint reliability.

Workforce: Ensuring the required resources and skills are available (often difficult to transfer open pit workforce to underground).

Moreover, awareness of time, which, once used, cannot be recovered.

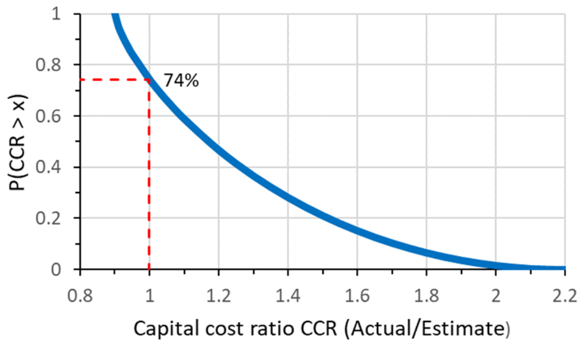

Figure 2 Probability of exceedance of capital cost estimates (after Bertisen and Davis, 2008).

3. CAVE PERFORMANCE

As shown in Figure 2, the probability that the ratio of the actual capital cost to the estimated capital cost of mining projects exceeds unity (i.e., a cost overrun) is approximately 74%. This result is based on mines built in the latter half of the 20th century when the average ratio was approximately 1.25. The situation has not improved in the 21st century. A recent McKinsey (2019) study showed an average ratio of 1.6, with up to 60% schedule overruns. It is considered that larger, more remote operations have contributed to this ratio increase.

Caving projects have a similar profile, with substantial costs and schedule overruns being incurred. Few caves have achieved the planned performance targets, underscoring the fragile nature of caving projects and often unrealistic initial performance expectations. The reasons for this fragility are varied; for example, insufficient orebody knowledge and limited understanding of cave mechanics are typically the reasons given for any shortcomings, but all too frequently, are a catchall phrase to hide other shortcomings. The technical challenges of caving are well known, if perhaps not necessarily well understood, and are reasonably well documented (Flores, 2019; Edgar et al., 2020; Simanjuntak, 2020; Casten, 2020). There is a substantial focus on cave performance in the study phase but less on construction performance.

Developing an achievable plan that sends the promised tonnes and grade to the mill safely and reliably is every planner's objective: plan the mine and mine the plan. However, to paraphrase Yogi Berra, *"In theory, there is no difference between theory and practice; in practice, there is," therein lies the rub.* The scale of operation, the volume of ground impacted by the caving process and the time required to construct have often underscored Berra's observation. Few cave mines, whether greenfield or brownfield, have met the expectations of the plan approved at the time of the decision to commit.

A review by the authors of selected projects suggests that 70 to 80% of the delay is incurred during the pre-production construction period, with some 20 to 30% during the production ramp-up period. Production setbacks occur during steady state but are fewer than during pre-production. For example, one caving project experienced a 60% increase in Capex, of which a significant portion can be attributed to the 40% increase in schedule from project start-up to target production. In turn, 80% of this schedule overrun can be attributed to delays incurred during the pre-production period and 20% during the production ramp-up.

A major contributing factor to such delays is the difference in information available to the project regarding ground conditions. The focus tends to be on the orebody and collecting data that can be used to assess cave design and performance. However, information on ground conditions for critical path access development away from the footprint is often limited, resulting in unexpected conditions and delays. Another factor is logistics. At one project, it was estimated that some 4 to 6 months were lost due to congestion underground.

Many technical lessons have been learned with respect to planned performance versus actual performance when transitioning from open pits to caving operations, and are summarised below:

***Lesson 1: Orebody Knowledg*e** is critical before deciding on transitioning. The rock mass characteristics and behaviour must be realistically measured, particularly in veined rock masses. An observation in several deeper mines is the reduction of open jointing and increased rock mass strength that occurs with depth, resulting in a move from joint-controlled failures near the surface to stress-controlled failure with depth. Exploration budgets must include the required level of geotechnical knowledge; grade and tonnage drilling results make for good press, whereas structure, jointing, and other geotechnical characteristics do not. The conditions through which access will be gained must not be forgotten.

Lesson 2: Organization, Culture and People. To have a culture and organisation focussing on overall production reliability (safety being given) that requires a planned process that will be scheduled rather than a daily reactive “firefighting” approach. A Responsibility, Accountability, Consult and Inform matrix (RACI) stating and informing are necessary. Unless correctly selected and well managed, people can represent the system's most significant uncontrolled variable risk.

Lesson 3: Time to First Ore and Production Ramp-up are major value drivers. Experience to date has been that projects typically deliver late. There is a scarcity of resources capable of developing deep, complex cave mines to schedule and quality. Too often, there is a failure to recruit and involve the operational team in sufficient time.

Lesson 4: Construction and Production Reliability: A Philosophy of Production (revenue) Reliability provides the framework for design and operation. Revenue from the cave depends on the reliability of the various excavations that enable the caving process. Recognising that excavations, whether on the footprint or critical infrastructure, represent a significant project investment and are critical assets that require monitoring and maintenance. Having drawpoints and MHS systems available for production is the value driver.

Lesson 5: Design, Cave Management and Operating Rules. Caving is a “fragile” process due to limited optionality once a commitment is made to a sequence and a layout. For this reason, a set of well-founded rules that inform the design and operational decision-making are required.

Lesson 6**: **Construction Quality is critical. For example, it is important to control overbreak during extraction-level development. Overbreak is often a result of ambitious schedules that result in construction shortcuts, the application of convenient and not necessarily the correct equipment, ineffective or poorly targeted contracts, and poor contract management. However, it all starts with a reasonable and appropriate design and schedule; what may be a good paper (or video today) schedule may not stand the test of the ground.

Lesson 7: The support of a cave footprint consists of two elements: the pillars, which must deal with the imposed abutment and cave loads, and the installed ground support, which is required to manage skin damage and can deal with the imposed deformations that occur during the caving process.

Lesson 8: Asset management and excavation health: Excavations are major assets. Monitoring and maintenance programs are required to maintain functionality. Mining-induced deformations bleed support capacity; thus, installed support may have a finite operating life, and additional support should be installed promptly. A Preventive Support Maintenance Plan should be developed before being required.

***Lesson 9: Measurement**:* Observe, monitor, and measure ground conditions and cave performance; undercutting should not commence until there is confidence that it can be suitably observed.

Lesson 10: Risk and change in risk must be communicated to senior management and the board (change management is not simply a site process). There are different stages in the development and operation of a cave, each with its own distinctive risk profile. Describing risks regarding potential construction delays, production interruptions and impacts on the business is important. However, the risk profiles are sensitive to changes in development (layout and sequence) and production (rate) plans; any significant change in or failure to follow the plan will change the risk profile. Once a base profile is obtained, a risk assessment associated with different production scenarios is required, not simply the normal flexing of production rates,

These lessons give rise to six guiding principles:

Value defines the business. Value can be expressed in different ways. Safety is an intrinsic value, as is economics. Without an appreciation of value, it simply is not possible to make informed decisions.

Safety is paramount. Safe systems create an efficient and effective working environment; safety comes first, and production will follow (safe production).

People are the key. A key lesson is the organisational approach required to manage up to 5 km of development a month (moreover, a development that must be to the highest standards in profile and complex support provision), introducing any new technologies and applying the rigour required in ramping up. This requires a fit-for-purpose organisation that drives a culture of collaboration, respect, and empowerment to act and make decisions.

Communication is critical across all functional areas. The ability to openly communicate with management, engineering, and the workforce on challenges and successes is key to the approach. Effective communication systems (e.g., 5G cellular services) enhance this ability.

Planning must be flexible to respond to cave performance and behaviour uncertainties. Production reliability and productivity ultimately drive the planning process.

Production Governance has a vital role to play in cave design, execution, and operation. A Panel provides the forum for resolving the conflicts that arise in design amplified by schedule pressures, the demands for revenue generation and the unforgiving nature of caving.

4. FRAGILITY

An aspect of caving not given sufficient attention is fragility. Fragility indicates how easily a structure can be broken (antonym: robustness) and damaged at a given impact level (Taleb, 2012). For example, vulnerable excavations are more likely to suffer damage, but fragile vulnerable excavations will suffer more damage than robust and well-supported vulnerable excavations.

Mining is recognised as a complex system (Perrow, 1986, 1999). The design, construction, and operation of a modern “multi-billion dollar” cave represents one of the most complex undertakings in the spectrum of mining. Fundamentally, caving is not a robust mining method due to the complexity, investment level, and limited options when things go wrong. This is particularly so during the construction and production ramp-up phases when the knowledge of ground conditions is limited, spending is high, and little revenue is generated. This is an aspect not well understood. While optionality is an aspect that quickly comes to mind (since the mine is tangible), an aspect not often considered is the role or influence that people play in developing and operating a cave.

As a cave moves from study to production, the options for change are continually decreasing, with the overall production system becoming increasingly inflexible and potentially more fragile; that is, production can become less reliable and more volatile. Uncertainty around orebody knowledge introduces variability in performance; thus, production tends to have an asymmetric profile with a fixed upside (typically determined by MHS limits) and a considerable downside, Figure 3.

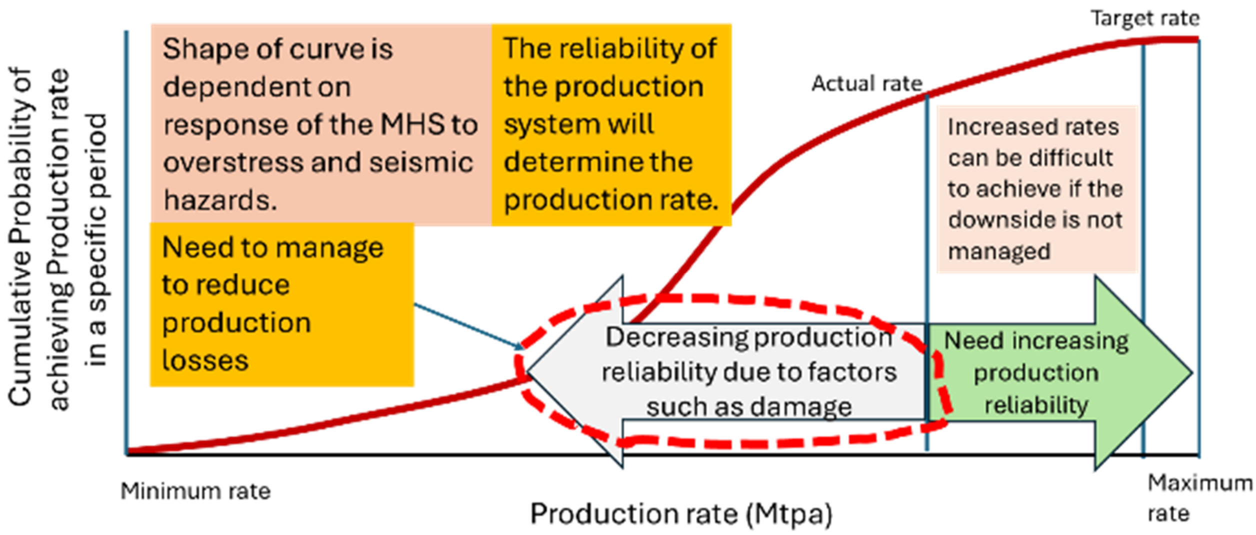

Figure 3 Asymmetry and variability.

Designers, constructors, and, more critically, decision-makers are wooed by the value proposition, which gets absorbed into the project mythology and can induce a belief in design, construction, and decision-making abilities, with the harsh reality of developing a cave being glossed over. This can result in the misalignment of agendas and tension between the various groups and, ultimately, the submission of an unachievable metal schedule. Human traits and how we organise ourselves to build and operate caves can contribute as much to the success or failure of an operation as the technologies or design methodologies used.

Part of the issue lies with the complexity of a modern cave, which designers must tackle. Equally challenging is describing the risks and opportunities to higher-level, often non-technical, decision-makers so they can decide wisely. A further challenge arises from the time horizons when bringing a large cave into production, which can stretch many years from initial concepts to attaining target production (Figure 4).

Designers, planners, and decision-makers rely on feedback loops to calibrate the veracity of their plans and decisions, and timely feedback becomes difficult in a very long-term project.

Without timely feedback against forecasts and expectations, the fragility of caving can be exacerbated by overly optimistic design and production estimates at the study stage that focus

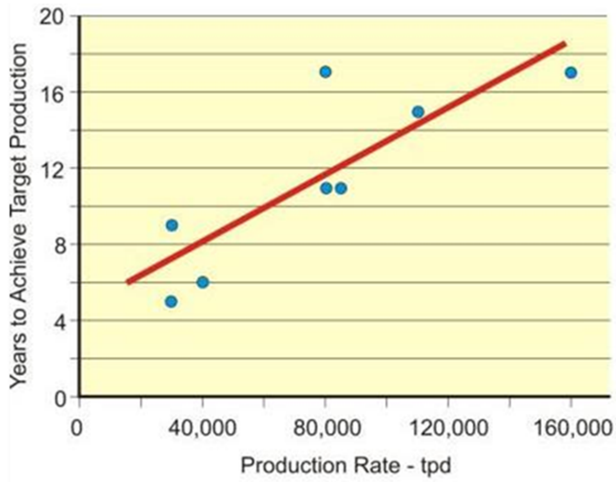

Figure 4 Production rate vs. time to achieve target production.

on specific economic criteria (e.g., the "imaginary" NPV mindset). The long timescale makes the knowledge (feedback) coming from other operations extremely important. Options can reduce the fragility of a system. Conversely, a lack of options makes a system more fragile (Flyvbjerg, 2017).

This gives rise to several questions:

Are we characterising the rock mass adequately, particularly given the value at risk?

Are the rock mass characterisation schemes adequate? Or do they give us a misleading level of comfort? For example, are the current rock mass classification schemes commonly used in the industry adequately describing the massive veined porphyries in Figure 5?

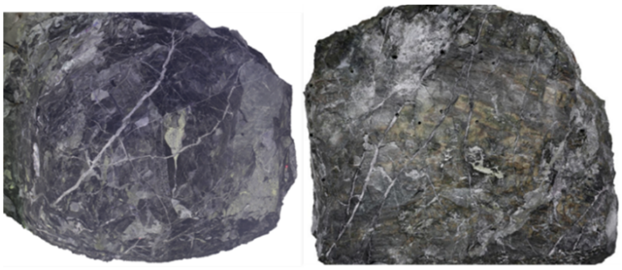

Figure 5 Examples of massive, veined porphyry masses in deep development headings.

Or are new approaches required to describe massive, veined rock masses? Bewick et al. 2022 used DFN modelling of veined rock masses at several caving operations to provide broad guidance on the potential consequences of fragmentation (Figure 6).

Should collecting geotechnical data for cave operations be treated with the same rigour as metal grades? And is a reporting code, like those established for ore reserves (e.g., JORC), required?

New approaches to assessing cave and cave infrastructure performance need to be developed, such as those proposed by Bewick, 2019 which indicates that massive brittle rock masses are less scale-dependent than jointed rock masses. The crux of the issue is the impact that veining can have on rock mass characteristics.

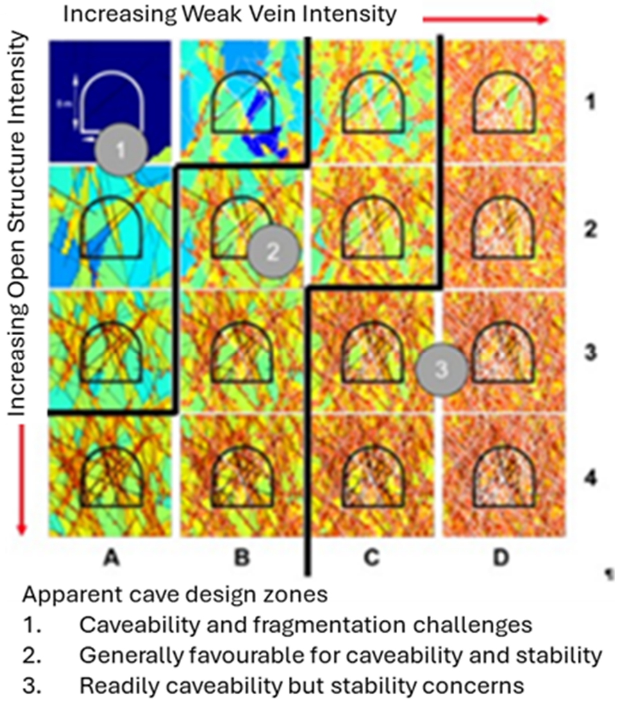

Figure 6 Improved description of the rock mass using DFN modelling (after Bewick et al., 2022).

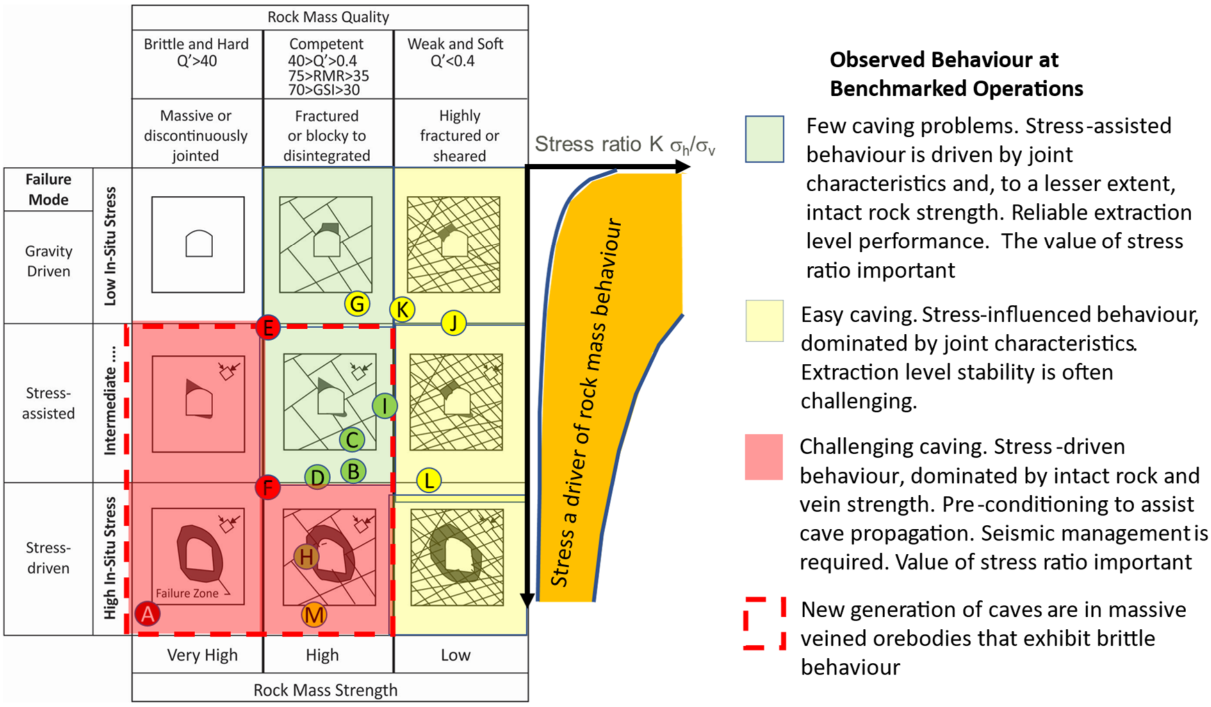

Figure 7 Must Match Design to Conditions.

Recent experience, as benchmarked in Figure 7, has been that the frequency of open joints tends to decrease with depth, and rock mass behaviour changes from one dominated by joint-bounded block behaviour to one dominated by vein and rock strength with brittle failure close to excavation or cave boundaries.

Understanding rock mass behaviour is key to a reliable design and assessing cave performance.

5. PRODUCTION (REVENUE) RELIABILITY

The objective is to achieve safe, reliable production and, in essence, to fulfil the promise to the shareholders. Production Reliability is a function of Footprint Reliability (drawpoint to tipple) and MHS Reliability (tipple to surface stockpile). Reliability depends on the performance of the physical assets in the mine (excavations, fixed and mobile equipment, e.g., chutes, crushers, rail, loaders, etc.) and, notably, the prevailing culture (behaviour), Figure 8.

The goal is to have a portfolio of drawpoints with sufficient redundancy to achieve the target production rate reliably. Footprint excavations represent a considerable investment and are a cave operation's largest physical asset outside the orebody. As such, they must be managed like all other major assets (e.g., fixed and mobile plant) to achieve the goal of Footprint and Production Reliability. Drawpoints and their associated extraction drives are major assets.

The various measures used in equipment asset management provide the framework for assessing footprint reliability; these include reliability, availability, mean time to failure and resilience. Footprint reliability is the probability that the footprint performs correctly during a specific period; that is, the target tonnage (at the stated grade and cost).

Equipment Asset Management typically monitors critical aspects of equipment, such as bearing temperature, oil analysis, wear, etc., to aid management. A similar systematic monitoring/measurement approach is also required to manage cave footprint reliability (Osario et al., 2020). The choice of the period over which to measure the production rate is important due to the impact of short-interval variability. Monthly or quarterly may be reasonable measurement periods.

Production resilience refers to the functionality of a system in relation to managing and mitigating production interruptions. Within this framework, resilience is a function of the time required for the system to return production to the target rate after a disruption.

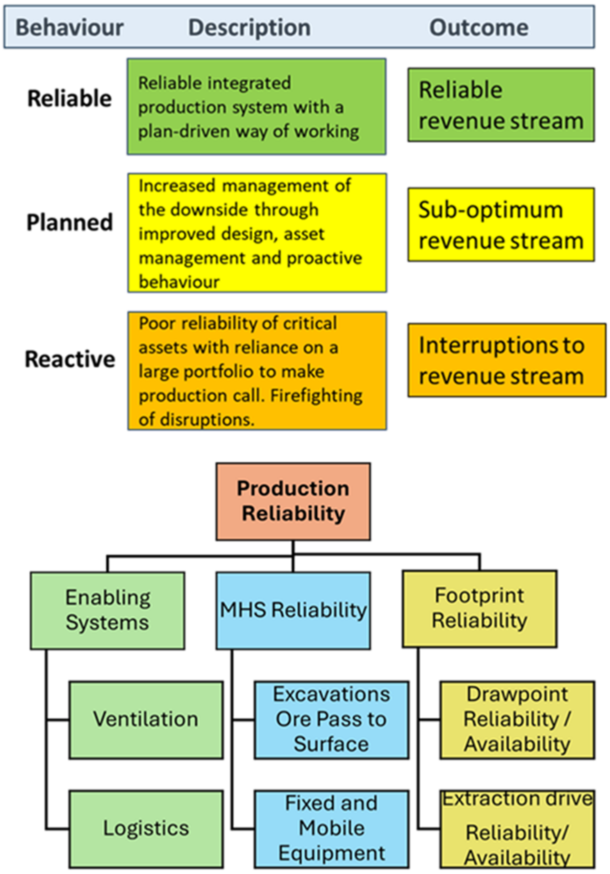

Figure 8 Process map for production reliability.

There are a limited number of drawpoints in a production block. This implies that the overall availability of the Extraction Drives must be high, probably equivalent to the availability of the MHS. The availability of individual drawpoints can be lower, but it is suggested that they should be greater than the availability of the loading fleet. When establishing footprint reliability acceptance criteria, it is recommended that a systems approach be adopted using tools such as Failure Mode Analysis (as per Asset Management) or Layer of Protection Analysis (as per Ground Control Management).

The above provides the input for a trade-off between the number of drawpoints in the portfolio, the corrective actions required (e.g., bigger pillars, additional support, smaller extraction drives/loaders), and the company's risk tolerance. It is important that when constructing early operational cost estimates, i.e., at the Study Stage, allowance be included in the budget for Ongoing Excavation Maintenance. Though accurate estimates cannot be made at this stage, the existence of a future requirement must be communicated to Senior Management.

6. DESIGN AND OPERATING RULES

The last 20 years have seen a substantial change in cave characteristics. Extraction levels are now considerably deeper, often at depths below 1,000m and lift heights have increased to 500m or greater (Cadia has heights more than 1,000m). These changes increase the demands on the extraction level. First, in terms of loads that the extraction level will be subjected to as the cave is established and propagated to breakthrough, and second, the operating lifetime of the drawpoint, expressed in tonnage drawn through the individual drawpoints. Complicating the issue further is the overall material flow and the ability to maintain even draw strategies over high lifts.

The question arises as to whether the rules established for interaction-based layout design still apply. Two interrelated, though somewhat contradictory, factors must be considered: footprint reliability and draw interaction. Experience at several high-lift caves has demonstrated the importance of footprint reliability; if a drawpoint is damaged, it is unavailable for draw. This has both an impact on production and maintaining compliance with the plan. Achieving footprint reliability drives wider drawpoint spacings. The downside is possible revenue loss later in mine life.

Footprint reliability can be thought of in terms of capacity and demand. Capacity refers to the productivity of the extraction level and its ability to deal with the demands placed on it by cave-induced loading and the wear and tear that results from moving a large tonnage from the drawpoint to the MHS. This typically drives wider spacing on the footprint to improve reliability, with the minimal ore loss occurring later in mine life being of less concern.

The trend is to increase drawpoint spacing, maintaining the extraction level's reliability and productive capacity. Conversely, the demand (recovery) is determined by draw interaction (and draw control). Draw interaction is a complex relationship between cave fragmentation, draw and lift height. Typically, simplifications are made to determine the diameter of the draw zone, a silo-like volume representing the ore that a drawpoint will extract. Experience, measurement and modelling that better simulate behaviour in the draw column indicate that reality is more complex and that revenue losses in high-lift caves with wider drawpoint spacings are less than previously thought. Wider spacings allow longer apron length, accommodating potential brow wear from the greater tonnage in high lift columns and other productivity factors.

Paredes (2022) assessed the recoveries for different layouts against the height of the draw, Figure 9. The work, based on measurements from operating caves followed by calibrated modelling of draw column behaviour, shows that the influence of draw layout decreases as column height increases. This is an important finding, providing the opportunity to expand layouts with the objective of increasing footprint reliability and productivity.

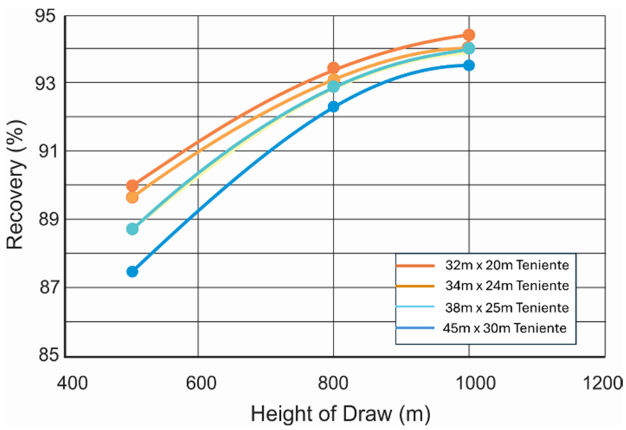

Figure 9 Recovery as a function of the height of Draw for various Drawpoint spacings (Paredes, 2022).

Ultimately, however, there is a trade-off between recovery reliability and productivity. Such a trade-off can be very time-dependent. For example, productivity can enhance value during payback.

7. CONSTRUCTION

How excavations are constructed is critical. Constructability must be integrated into the design and implemented rigorously to ensure development efficiency, operational effectiveness, and reliability. Trade-offs in the construction schedule and operational reliability must be made based on sound engineering principles, including support design. Far too often, Project Schedules drive ineffective construction practices. Shortcuts are taken to achieve efficiencies that satisfy (unrealistic) schedules, compromising the long-term effectiveness of the installed support and, ultimately, the ‘health’ of the asset. For example, good drill and blast control are essential to reduce overbreak, maintain designed pillars and allow reasonable support placement regimes; however, unsuitable drilling equipment is frequently applied for convenience. A further benefit of good drill and blast control is reduced costs due to the reduced haulage of overbreak material, a benefit often neglected.

More specifically, managing overbreak and peripheral blasting control on the production footprint is more important than in other parts of the mine, such as sections of the MHS (where underbreak can be more critical). The extraction drives and the drawpoints have a duty and service life that is a function of the rock mass within the pillars that comprise the footprint. Overbreak and peripheral damage can reduce overall performance, becoming increasingly more important as the depth of mining increases.

8. ASSET MANAGEMENT AND EXCAVATION HEALTH

In a modern caving operation, the production footprint and the mine infrastructure excavation are significant investments, far greater than the investment in fixed and mobile equipment. The various drifts are used by mining equipment to conduct tasks such as ring drilling, ring blasting, and the mucking of draw points, and, therefore, need to be maintained to reduce the risk of ground-related production interruptions.

The mine development tasks are linked to a mine plan and schedule to develop a revenue forecast, informing shareholders and investors of possible forward-looking results. In developing the schedule, it is common for discrete event simulations to be carried out to model equipment movements, breakdowns, and resourcing requirements. These simulations attempt to ensure that the selected equipment has the efficiency needed to achieve the desired ore production schedule reliably. While this aspect of the production design is robust equipment-wise, the most critical piece of infrastructure required to meet production targets cannot easily be considered in these simulations, that is, the production footprint itself.

Standard measures used in asset management, such as availability, utilisation, and mean time to repair, must be developed to monitor excavation performance over time. This will ensure that any interventions are implemented in time to achieve the operational efficiencies required for reliable production.

In shallower mining environments, designing an initial drift/support system for a cave footprint may allow it to remain reasonably stable for its operational life. In deep mining conditions, this is not feasible, no matter how much support is applied. At depth, drifts converge, support is consumed and must be replaced. Drifts need to be maintained, ideally in a planned manner, but at times due to unexpected incidents (such as seismic events) in an unplanned manner. Underground excavations must be treated as any other capital asset in the operation.

Current practice is typically reactive, where little is done until damage occurs. Such an approach increases the likelihood of a safety interaction and results in production interruptions, leading to revenue loss. Excavations must be treated similarly to fixed and mobile equipment in the mine, where the objective is to have a reliable system based on a robust regime of performance monitoring and planned maintenance. The objective is to reduce the number of production interruptions due to unplanned repairs by implementing a planned drift monitoring and maintenance program. The first step in such a change is to measure:

Quality is how well the drift is initially constructed. It is important since it will impact the drift's reliability and repair. However, too little attention is commonly paid to QA/QC during construction.

Availability is the proportion of the time that the drift is available for its intended purpose.

Utilisation is the proportion of the time that the drift is available and used for its intended purpose.

Reliability describes how often the drift does not fulfil its intended purpose, usually measured by the mean time between production interruptions and the Mean Time to Repair – i.e. the average time required to bring production back online.

The extraction level and undercut will strongly influence a cave mine's production reliability and form an integral component of any material movement assessment. Shallow mine learnings do not apply to mines operating in high-stress conditions. The industry must update the design process to meet the new challenges.

As induced stress levels increase, brittle rock masses become increasingly vulnerable to damage, Figure 10.

Once a critical load and deformation stage is reached, damage ensues. The transformation from a 'massive' to a 'damaged' rock mass is irreversible, fundamentally changing the excavation behaviour and support requirements. This fragility and the associated failure processes of brittle failure and bulking ground drive the need for deformation-based design. For example, the condition of the walls of an excavation is a function of applied stress and intact strength (i.e., as the intensity of jointing tends to decay with depth). Thus, intact rock strength can become the key measure of rock quality. It is suggested that operationally, an excavation moves from robust to fragile at the onset of moderate spalling and bulking. The increased bulking associated with spalling increases the demands on the installed support, resulting in an increasingly fragile system.

Support is installed to provide safe and functional excavations; however, support comes with cost and schedule impacts. The authors' experience is that rock support installation in the development cycle can account for up to 50% of development costs and between 30% and 50% of the development cycle (often more on a cave footprint). In contrast, inadequate support in key development can result in damage and costly value reduction (production interruptions/revenue losses).

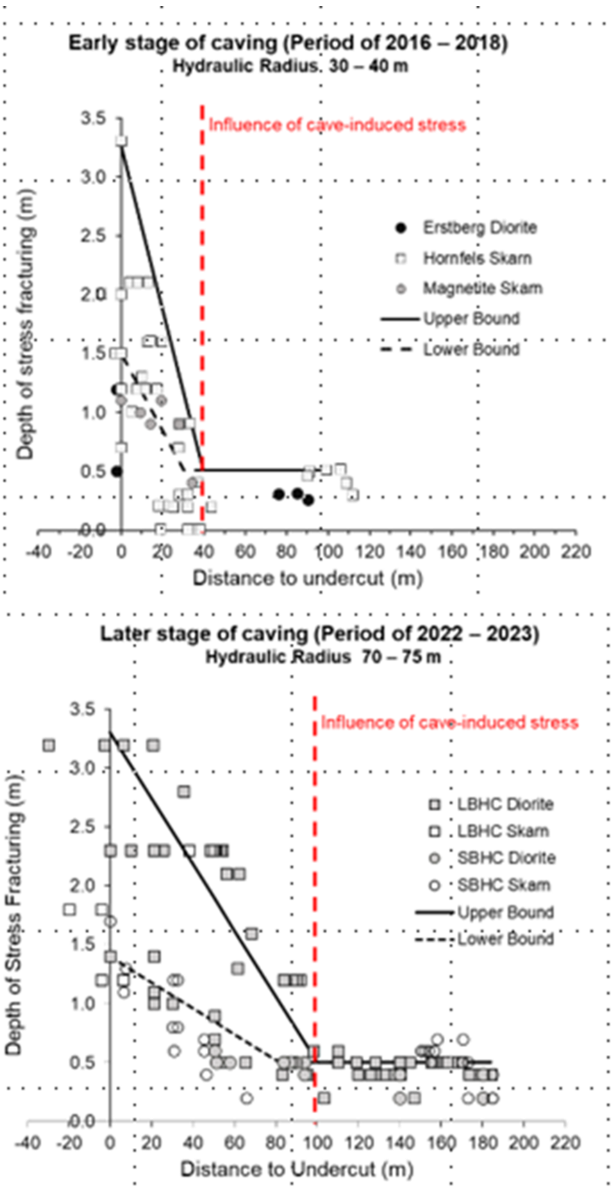

Figure 10 Depth of fracturing and wall displacement versus distance to undercut (after Primadiansyah, 2023).

9. ORGANISATION, CULTURE, PEOPLE

Developing a cave requires decision-making under complex and uncertain conditions. Any silos that exist tend to amplify human traits such as hoarding information, a natural tendency to withhold bad news and the general information churn that occurs in any large organisation (Pitzer, 2006). This can result in poorly informed decisions that impact the business. Without going into too much detail, cave design is just the start. Management takes over once the cave is initiated, often with conflicting agendas.

Reviews of caving operations have highlighted that culture, in its various forms, significantly influences caving, ground control, seismic hazard and the likelihood of production interruptions. Often, different agendas exist for corporate, operations and cave management. These give rise to decisions that can be short-term, with limited recognition of the overriding cave performance. This can have unwelcome consequences. Cave behaviour trumps metal scheduling and production imperatives.

Technology and innovation have come to the fore but are not robust solutions unless an appropriate structure is in place to support the required changes. There is a dichotomy in the industry with some technologies, such as automation, being adopted and adapted but with continuing resistance to others, for example, the acceptance of drill automation and the advanced communication systems central to rapid development. Humans are typically slow to accept change, whether doing a task differently or introducing new concepts and ideas.

Only when there is a “burning platform” does change happen rapidly. Indeed, the human component is more important than ever, with questions on how decisions get made around applying complex and sophisticated technologies and how the perception that technology will solve the problem – the “silver bullet” belief – should be handled.

Thus, the question arises whether the right organisational structure is in place to deal with the necessary changes to reduce the delays and cost overruns synonymous with the caving industry. Complexity is the burning platform that must be addressed if the next generation of deep, high-capacity caves is to be successful. The first step is acknowledging that caving is fragile with strong downside asymmetry. This provides the framework for organising and developing the cultures required to upgrade information collection, design, construction, and operational approaches.

The second step is to acknowledge that cave mines are changing as they become deeper (different rock masses, higher stresses, and different rock mass behaviour), necessitating a design methodology change – the rules developed for shallow caves are consistently shown not to apply. This is followed by the requirement for much more rigorous construction and operations planning that incorporates lessons learned from those caves currently under construction. It is essential not to take shortcuts because experience has shown that the cave always wins when shortcuts are taken.

Caving operations face the challenge of achieving the plan by providing the promised tonnes and grade to the mill safely, reliably and at the stated cost. The first part of the challenge is developing an achievable plan, followed by the second challenge of implementation, **“Plan the Mine – Mine the Plan”.**

The culture of production is a key consideration. Production crews often work alongside development/construction crews in a panel cave, completing a complex system of closely spaced tasks and proximate production steps with unfamiliar or unintended feedback loops—for example, seismic damage and the need for cave shaping resulting in production ramp-up delays.

Other constraints include resourcing (people, equipment), logistics, and costs. All this makes the system complex, uncertain, and fragile. Management must make important decisions impacting the long-term business, which must be done in the face of stress and uncertainty. Decision-making under stress, uncertainty, and complexity is difficult, and only the right culture can simplify this.

10. CONCLUSIONS

Caving is a risky business with surprises that are generally not well-recognised or articulated. As projects become deeper and increase in size, they become more complex. Often, substantial organisational optimism exists, particularly at the design and project stages. Therefore, effective controls against optimistic biases are required. It is about people and how forgiving the orebody is.

Because of the perceived low operational cost, there is a tendency to apply the caving method to very marginal projects to reach an encouraging result. However, the method is not suited to very marginal projects due to the significant capital cost and the overall risk profile, which is typically asymmetric with limited upside and substantial downside. The mining teams need to be able to access and establish the cave faster. This requires a fit-for-purpose design, which in turn requires better orebody knowledge and rock mass characterisation as the cornerstone of better mine design and improved predictions of cave performance.

The game is changing, and the approach to cave design, construction and operations must change, too. The convenience and simplicity of a rock mass classification to determine caveability and other performance parameters are very appealing, and it is easy to become lulled into its abuse. However, the experience of deep, high-production caves is sobering. The mines have changed due to depth and size; the design approaches must also be adapted, as appropriate, to ensure safe, reliable production that addresses the economic imperatives.

A key issue, complexity, is the burning platform that must be addressed if the next generation of deep, high-capacity caves is to be successful. The first step is acknowledging that caving is fragile with strong downside asymmetry. This provides the framework for organising and developing the cultures required to upgrade the design, construction, and operational approaches.

The second step is to acknowledge that cave mines are changing as they become deeper (different rock masses and different rock mass behaviour), necessitating a change in design and operational methodology; the rules developed for shallow caves are consistently shown not to apply. More rigorous investigation, construction and operational monitoring and planning incorporating lessons learned from those caves currently under construction is required. Finally, it is important not to take shortcuts because experience has shown that the cave always wins when shortcuts are taken.

The comments above are a mixture of strategic and tactical views building on the realisation that deeper production gives rise to excavations vulnerable to ground conditions (brittle failure), which, with limited optionality, results in an inherently fragile method (caving). A robust engineering approach is required to develop fit-for-purpose designs catering to the caving's inherent fragility and the business' risk tolerance.

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