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ABSTRACT

Assessing the viability of a mineral resource for block cave (BC) mining at depth presents a complex challenge. During early study phases, the scarcity of rock mass data and the extensive caving volume, contribute to the challenge. Consequently, there is a significant risk of misrepresenting the rock mass variability, which impacts the forecasting of caving hazards and consequently the downstream design of strategic mitigation controls. To highlight these challenges, this paper focuses on the common hazard of cave propagation and presents a review of published case studies. These examples include five hard rock block and sub-level caves (SLC) initiated at depths ranging from 500 to 1200 meters below the surface. Key considerations for the strategic assessment of caving hazards, based on insights from the case study review are presented for consideration. The proposed considerations aim to provide cave designers with a framework to developing a strategic design process including a basis for data sufficiency.

1 INTRODUCTION

Mining companies are seeking to understand potential mine feasibility to enable prompt decision making and capital allocation. Due to depletion of near surface resources and disseminated grade, many of these new projects require cave mining methods for exploitation due as it offers the necessary lower operational costs and associated high production rates, to turn resource into viable reserve. Predicting the viability of a hard rock cave mine at depth is difficult because:

- Drilling at increasing depth to gather the required data is challenging, costly and time consuming, with no industry guidelines outlining data sufficiency, outside of resource estimation.
- The design methods effectiveness is limited due to overly simplified assumptions, a lack of rock mass sub-domains, and lack of alignment on the right data at the right time.
- Cave performance is difficult to control after initiation, with (Lynch, et al., 2018) describing the need for careful monitoring to understand cave shape and growth to manage safety and economic consequences.
- The project cycle through studies, execution and depletion is generally decades to obtain learnings.

This extended ‘feedback loop’ makes deep cave mines challenging to optimise and iterate to suit local conditions. This results in a reliance on empirical methods and benchmarking (noting that all mines have unique conditions and challenges). In early phases of study with immature Total Deposit Knowledge (TDK) (Chitombo, 2011), it can be challenging to foresee how potential risks may manifest and attempt to quantify the potential impact on the business. The risk profile can be exacerbated with increased depth and subsequent volume. In the absence of data for detailed engineering, this phase is when divergent thinking is required. For the most successful cave mines, hazards are identified early, and effective strategic and tactical controls are applied. Dunstan & Power (2003) illustrated the controls required to manage the technical risks of the Ridgeway Sub-Level Cave when it was beyond the current state of industry practice, providing a prominent summary within literature.

2 DEFINING CAVABILITY WITH LIMITED DATA

Modern caves are now being planned in different conditions to those in which many historical caves have been mined. At some point, the combination of both increased depth and more competent rock mass has the potential to alter design requirements outside the bounds of previous assessment methods. Datapoints that formed the basis of empirical assessment methods may not reflect modern caving conditions. Existing benchmarking noted a trend in block heights with average block heights varying from 100m to 250m from pre-1970 to post-1990, respectively. With block heights up to 500m being planned (Flores & Karzulovic, 2002). This trend in modern cave mines has resulted in challenges for practitioners to continue to assess cave behaviour. At the same time, yesterday's state-of-the-art considerations are today's business as usual practices. During mining method selection studies, this initial cavability assessment often coincides with a low level of data and understanding, particularly around TDK, however, one must still use the available design methods and explore the viability of mining options.

2.1 Existing early phase estimation methods

The factors influencing caving have been widely explored and are well documented, (Bartlett, 1998), (Mathews, et al., 1980); (Laubscher, 1994); (Laubscher, 2000); (Mawdesley, et al., 2001); (Beck, et al., 2011). Rock mass caving is initiated at any depth underground by developing an arrangement of horizontal drives connected by sequential blasting and material extraction. The arrangement of these drives themselves must be such that they remain stable whilst the material above caves. This process undercuts the orebody and caving begins when sufficient span has been generated relative to the orebody characteristics (in-situ stress, rock strength, number/orientation/type of fractures, major structure, etc). Continuous caving is enabled by creating void by drawing material from the level(s) below. Cave progression may stall due to a change of rock mass characteristics and/or stress conditions. The importance of geology as part of cavability prediction and performance is highlighted by Morales et al (2023). Understanding how the conditions change throughout an ore column and overlying units is critical for defining cavability at depth. This is an obvious but potentially overlooked item at early study phases where focus can be constrained locally to the undercut elevation.

The state-of-the-art for assessing cavability noting the challenges of using different empirical methods and numerical models are summarised by Morales et al (2023). They are influenced by the data quantity (sufficiency), data quality (precision and accuracy), data distribution, and the inherent variability of rock mass. The combination of data insufficiency and lack of precision results in uncertainty, or epistemic uncertainty, whilst the natural randomness of homogeneous rock results in variability in the captured data. The impact of these two factors (uncertainly and variability) being unpredictability (Bedi, 2013). It is this uncertainty and variability that leads to overly simplified and conservative assumptions such as the lack of rock mass sub-domains, which can lead to overly simplified caving estimations applied over large volumes.

Why is this important? The first question that is often asked in caving studies is "what is the Critical Hydraulic Radius (HRcr) required for caving?" This can be assessed using empirical methods or numerical simulations. These charts provide an estimate of the potential for a rock mass to cave under a certain condition. A state of caving, transition, and stability relative to the rock mass and opening size can be estimated. However, the effectiveness of empirical cavability assessments can be impacted by averaging the rock mass properties across the orebody and the limited data set upon which the empirical models were built, which may not represent the deep, high stress, competent conditions, now being considered.

More sophisticated numerical methods can suffer the same fate regarding heterogeneity not included in the model through lack of definition. This can limit the imagination of scenarios or outcomes that can occur up the cave column. This becomes of particular interest over the height of the cave column when there are a variety of rock mass domains.

As an example, (Lett, et al., 2016) demonstrate the importance of identifying unique domains and the controls that were required to manage a more competent porphyry above the cave column to enable cave breakthrough to surface. The identification of unique lithology influencing cave performance often does not occur early enough in a study phase resulting in insufficient control definition. This is important as empirical design methods generally take a binary view of cavability (i.e. cave vs no cave with a transition zone of uncertainty) whilst numerical methods lacking domain definition can show-up as either overly optimistic (vertical caving) or pessimistic (no caving). A simplified empirical chart is shown in Figure 1 alongside a vertical section through three units to demonstrate:

A. Undercut geometry and rock mass classification of an example cave.

B. Cave propagation through a unit with lower rock mass classification and a reduction in geometry.

C. Cave propagation into a unit with higher rock mass classification and further reduction in geometry. Entering the transition zone.

D. Cave propagation through a unit with lower rock mass classification assuming a vertical cave break angle.

E. Cave propagation through a unit with higher rock mass classification assuming vertical break angle.

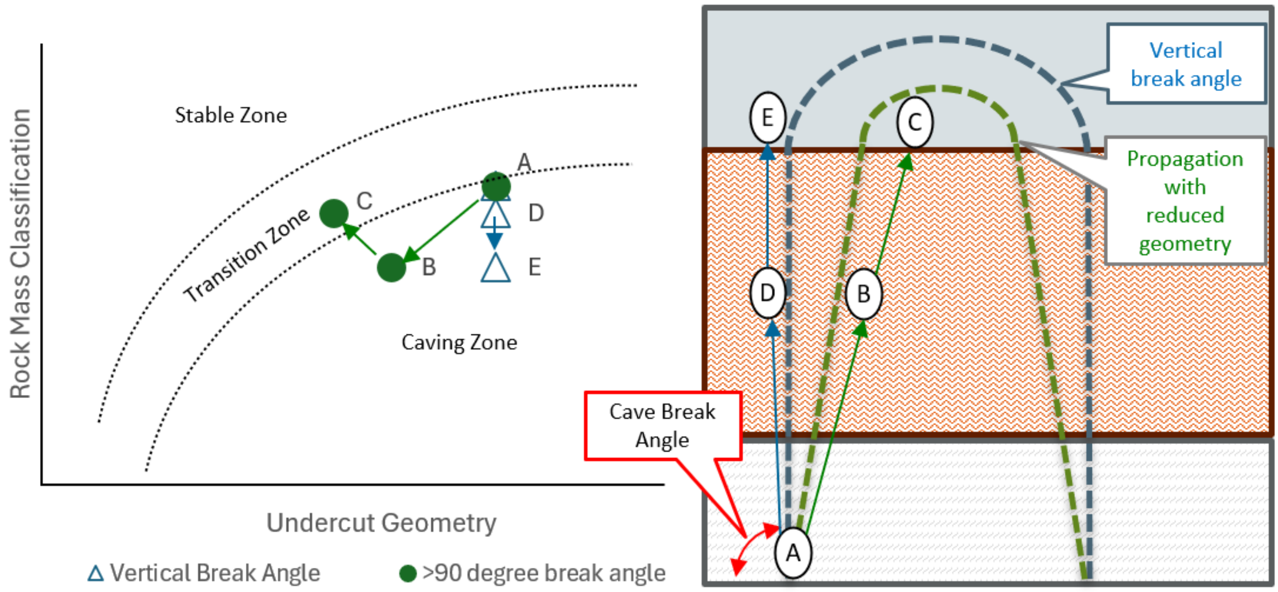


Figure 1 **Cavability chart considerations.**

This example demonstrates an outcome similar to that experienced within several of the hard rock cave case studies discussed in Section 3 whichCAVING CASE STUDIES – HARD ROCK CAVES AT DEPTH show an arched profile or overhang (cave break angle exceeding 90°) at some stage. This effect may have potential to compound over vertical extents and push more domains into the transition zone and towards the stable zone indicating potential cave stall. Therefore, instead of a single point average estimate, cavability must be considered for a range of rock mass classifications, reflecting the uncertainty and variability in the data set and through the entire caving column. The hydraulic radius to propagate the cave must be based on the highest MRMR zone wherever it may be (Laubscher, 2000). Consideration for alternate geometries throughout cave growth should also be assessed. Developing this understanding in an early study phase is a crucial step to develop appropriate inputs to empirical methods and numerical models so that potential scenarios are imagined and thus managed.

3 CAVING CASE STUDIES – HARD ROCK CAVES AT DEPTH

3.1 *Summary of Case Studies*

The case studies presented below and illustrated in Figure 2 all had varying geology, rock mass quality ranges and local conditions. The images shown are illustrative of the cave at a given state of time in available views. Individual papers can be referenced for detail on each specific cave. General observations of the case studies are:

- Each cave experienced some form of arching or asymmetrical cave path.
- Implementation of cave stimulation activities was common to assist propagation. Both pre or post initiation.
- Footprint geometry modifications are observed in some cases to promote caving.
- Cave shapes evolve throughout cave maturity as per E48 snapshot (extraction drives added aiding lateral growth).

The rock mass volume over which caving occurs is massive making tactical controls difficult to deploy. For comparison, a stable open stope is shown in which tactical controls are more easily implemented and more effective. The insights gained from the case studies highlight how the scale of deep hard rock caves require more emphasis on establishing appropriate strategic controls to manage hazards such as:

- Enhanced early geotechnical model definition to identify heterogeneity,
- Footprint expansion design contingency,
- Rock mass engineering.

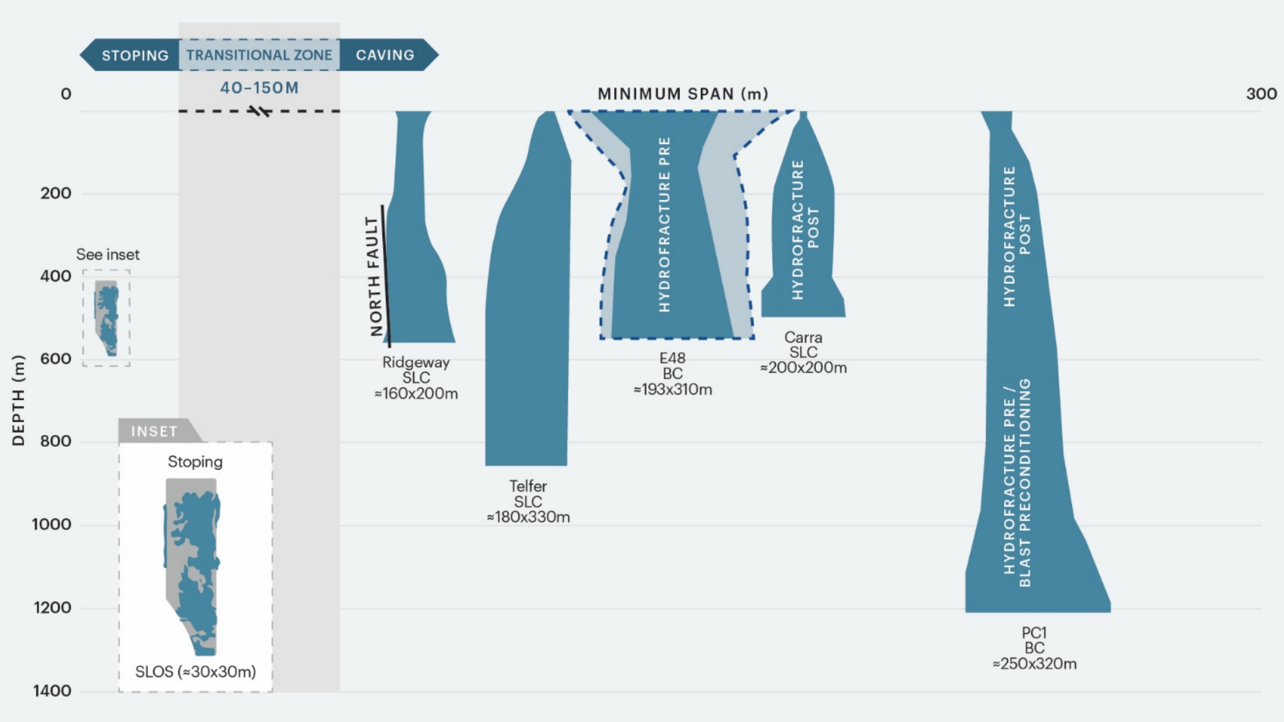


Figure 2 Schematic of mined caves.

The key local factors that influenced cave performance in the specific case studies are noted below:

3.2 *Carrapateena*

- Local factors: contrast in strength of domains, performance of cave in highly horizontally laminated weak rock mass, (Balog, et al., 2021)
- Initiated in the Carrapateena Breccia Complex the cave propagated well through the lower units. It then rapidly grew through the Woomera shale, where it

remained for approximately 6 months until cave stimulation activities occurred.

3.3 Northparkes E48

- Local factors: Hydrofracturing of the cave column from surface, (Snyman & Webster, 2022), (Sagawa & Yamatomi, 2009) and (van As, 2021).
- Rapid breakthrough to surface, believed to be aided by hydrofracturing and persistent near vertical faults across the orebody.

3.4 Cadia PC1

- Local factors: Deep undercut level with intensive pre-conditioning, additional span added during construction, cave narrowed in strong units, (Lett, et al., 2016).
- Caving slowed upper cave column, initiating a Trigger Action Response Plan (TARP). Surface hydrofracking and targeted draw in the additional span was undertaken to assist the cave in propagating to surface.

3.5 Ridgeway

- Local factors: Known faulting to assist caving, (Dunstan, 2016)
- Mine scale structure (North Fault) was present through much of the cave column, which assisted with cave propagation. The cave propagated to the surface in less than half of the anticipated time.

3.6 Telfer

- Local factors: Blocky environment and well jointed rock mass, (Giovinazzo & Singh, 2010).
- The rock mass quality above the undercut was controlled by lithology, the Main Dome hinge resulting in a well jointed rock mass which promoted caving.

4 CAVABILITY – STRATEGIC PLANNING CONSIDERATIONS

The four key risks for caving projects are noted by (Butcher & Fallon, 2011) as corporate appetite/attitude, corporate investment evaluation criteria, cavability risk and key commodity and operational costs. Therefore, the mine planning technical focal point for strategic planning should commence with cavability. Several of the case studies demonstrate that strategic controls must have robustness relative to the confidence in TDK data definition.

Within cavability risk, there are several key strategic decisions, such as mining method selection (SLC/BC/Panel Cave, Macro-block), draw strategy (including production rate and linked to caving method), undercut elevation, initiation point and undercut geometry. It is important to note that the above parameters are not exclusive decisions. All these parameters are interacting with one another and cannot be solved or assessed independently. (Dunstan & Power, 2003) demonstrated the importance of this for a successfully executed sub-level cave. This approach helps mitigate any anchoring bias which may show-up in a studies selection process.

“A smart and robust strategic plan is vital for the success of a business. The aim is to harness the deposit variability and develop dynamic planning policies to add value” (McQueen, n.d.)

The above statement is taken from an open cut mining context; however, the mention of ‘robust’ and ‘harness the deposit variability’ seem extremely relevant to early phase deep cave studies.

4.1 How much data?

As exemplified in the previous section, the impact of localised geotechnical & geological factors can have profound effects and that TDK data is essential for the effective application of safety in design practices. However, it is a commonly asked question of mining geoscience disciplines, “how much geoscience data is required for a mining study?” Unlike the Mineral Resources and Ore Reserves (MROR) process, which has well defined guidelines on data sufficiency in the various reporting guidelines (JORC, NI 43-101, & SAMVAL), there is no such industry or regulatory standards for Geotechnical data in relation to mining studies. In their absence, a few authors including (Steffen, 1997), (Haile, 2004) and (Cepuritis & Villaescusa, 2012) have all presented frameworks to define minimum requirements. Authors (Read & Stacey, 2009) in their open pit guidelines book present guidance on this matter based on data confidence levels, which can be determined statistically or categorically. Under the proposed guidelines, as project stages evolve towards operations (execution), data confidence levels across data models increases.

As part of this paper, the authors introduce an adapted version of the original guideline by Read and Stacey, designed for consideration in underground mass mining projects, see Figure 5.

The framework provides guidance on target model confidence levels, for each study phases, whilst recommendations are also provided as to the stage at which known geotechnical hazards must begin to be assessed. To have assurance in the identification and quantification of caving hazards, through analysis and interpretation, sufficient data confidence, as presented in Figure 5 is critical. It should also be noted that hazard assessment and design of mitigation controls, must continue to be refined during future study phases, as data quantity and confidence grows, and hazard forecasting maturity develops towards forecast aided design and quantifiable risk.

Further to the provision of a target level for model confidence, the framework can be used to highlight miss-alignment between current model status and the project stage. The structural geology model for example may be assessed as pre-feasibility (Level 2), whilst the study is progressing through the execution phase (Level 4). This may prompt an appropriate response, in the form of additional drilling and data collection, or the application of conservative inputs resulting in conservative designs (Dunn, et al., 2011). The framework thus provides a common categorisation and nomenclature that those involved in cave mine design and planning can use to communicate uncertainty and data sufficiency through the design phases.

4.2 Timing for scenario development

The ability of the study team and organisation to identify and manage the key strategic decisions, providing appropriate robustness of alternatives is crucial for setting up the project for future phases. (Hall, 2014) places great emphasis on the rigour required in the preceding prefeasibility study stating "if the best strategy has not been identified by the prefeasibility study, and becomes the focus of the feasibility study, it is unlikely to be found during the feasibility study. Wholesale changes in strategy at the feasibility stage are unacceptable, and as such a comprehensive option analysis is required at the prefeasibility stage to ensure to correct business case is chosen." This concept is well illustrated in Figure 3 with study quality and decision-making being the differentiator in early study phases, to set the project on a trajectory to retain and maximise value through to realisation in operations.

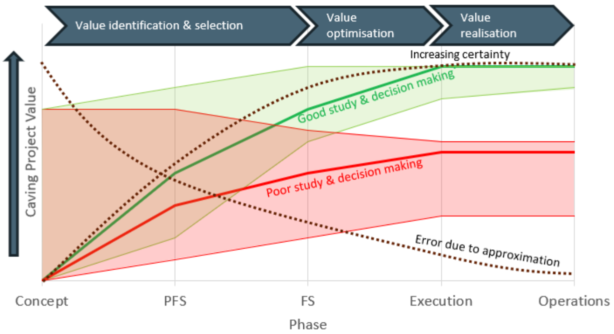


Figure 3 Project value, uncertainty, and control effectiveness.

It is logical that a study team focus on the relevant control measures or engineering solutions to honour the current state of input data and relative effectiveness within the accuracy of outcomes. This allows foresight of the future states of data maturity and ongoing consideration of controls. Suggested control measures for a deep caving project are shown in Figure 5 showing how detail and maturity may be increased throughout the project cycle.

The controls defined as 'strategic' are those which have increased control effectiveness on the available outcomes and warrant additional consideration within study phases. These strategic controls form the foundation of the caving study and value proposition. At each step or review of data, the above considerations can be evaluated in an ongoing cycle with the aim to reduce variability in the key impacts to cavability as outlined in Figure 4.

Contrasting to this, tactical/operational decisions while initiating the cave and/or during propagation, have a much smaller time window to review, react and respond. The control measures available to the execution team are limited, may take time to implement and might have limited control effectiveness. Strategic decisions with more extensive time frame to execution, leads itself to focusing on elimination, substitution, and engineering controls, which are higher order, whilst tactical controls are more administrative as cave designs once set can be quite rigid to change. This highlights the importance of identifying and exploring the various potential caving scenarios, to allow for appropriate monitoring, early identification, and appropriate mitigation.

While an operational phase should assess and ideally re-validate the assumptions made in the strategic phases, it should not be limited by them. Despite the time frame for decision making being short, the operational review is key as it is one of the last lines of defence and likely has far more mature data to inform. At this stage we deal with reality, what is experienced does not always match what was assumed during study phases.

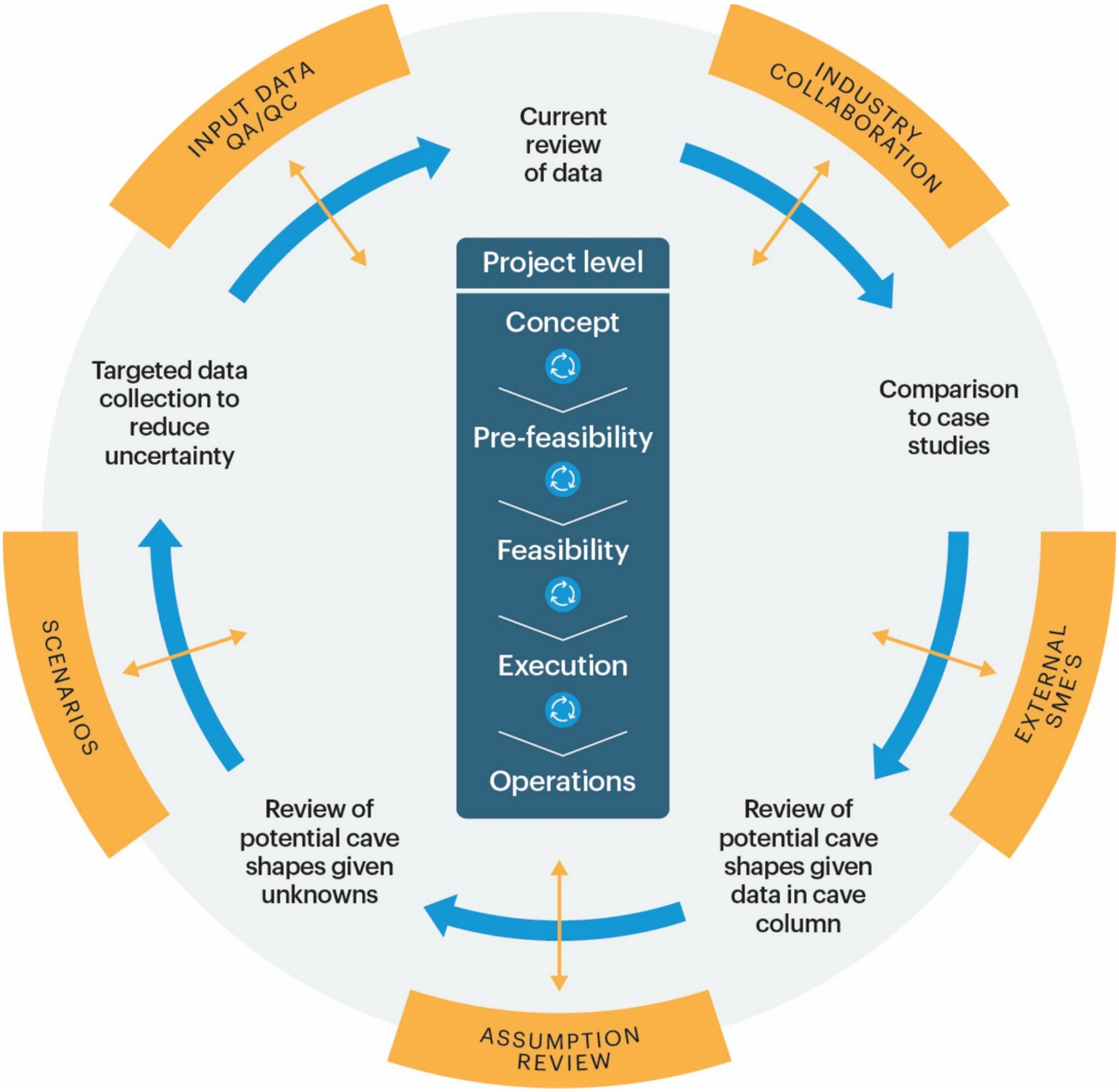
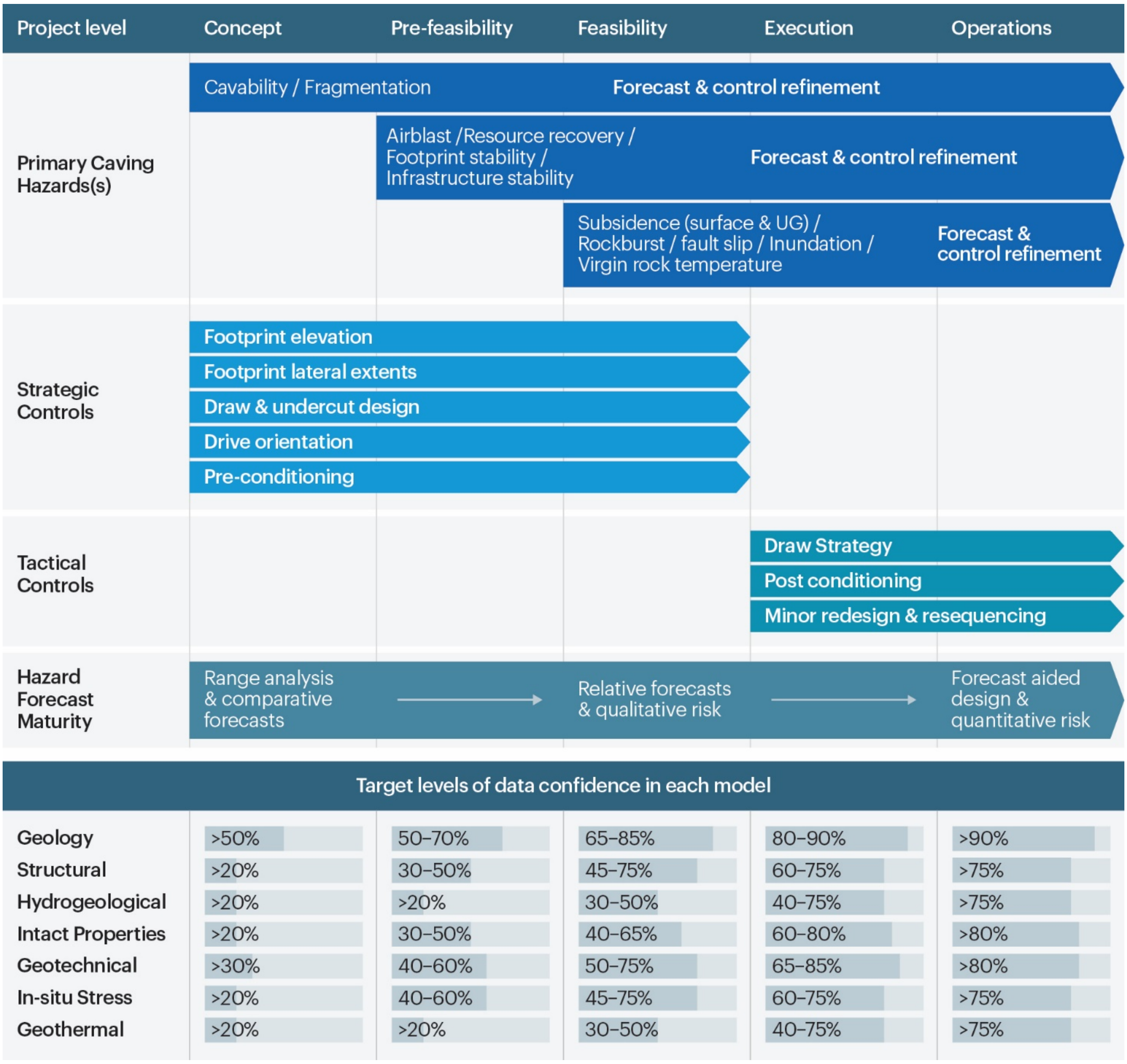


Figure 4 Caving project design cycle.



	Concept	Pre-feasibility	Feasibility	Execution	Operations
Geology	>50%	50–70%	65–85%	80–90%	>90%
Structural	>20%	30–50%	45–75%	60–75%	>75%
Hydrogeological	>20%	>20%	30–50%	40–75%	>75%
Intact Properties	>20%	30–50%	40–65%	60–80%	>80%
Geotechnical	>30%	40–60%	50–75%	65–85%	>80%
In-situ Stress	>20%	40–60%	45–75%	60–75%	>75%
Geothermal	>20%	>20%	30–50%	40–75%	>75%

Figure 5 Design cycle and data maturity, modified after Read & Stacey, (2009).

4.3 Scenario trade-offs

Imagining different potential cavability scenarios through rock mass domain and structural hypotheses is required to make an adequate trade-off of strategic controls (e.g. block height, geometry, and mining method). For example, a scenario targeting a high-grade portion of an ore body at a reduced span must honour the early data uncertainty such that a range of geometries and other cavability controls are identified and assessed to enable a fair mining method comparison. If this is the sole scenario carried through a study phase, there is significant risk of re-work once additional detail is ascertained or in extreme cases a greater impact that may threaten the overall viability of the project.

Impact of cave underbreak on recovery is documented throughout caving literature (Burgio, 2020) (Bennett, 2020) (Bennett & Fowler, 2022) and is namely applicable to the BC method (including panel caving) which relies on the ongoing caving process to create broken ore stocks. In the context of early study phases with significant overburden and uncertainty, there is likely to be insufficient data for meaningful computer simulations prior to initial scenario definition. An approach is to hypothesise what the simplified cave shape outcome may be and apply a constraint to the plan to initially capture this modifying factor. This process does provide consideration to cave shape outcomes but may be viewed with a positive lens if applied at all. This may assume successful caving outcomes with subsequent minor application of modifying factors.

The following sections discuss a simple set of example scenarios with application of strategic controls (undercut elevation and geometry) to assist thinking at an early study phase. These can be further assessed with comparison of production schedules and economic analysis using various tools.

Four hypothetical BC scenarios are shown in Figure 6 and Figure 7:

1. Double lift BC
2. Single lift BC
3. Wider single lift BC (additional drawbells)
4. Overhung/under broken wider single lift BC

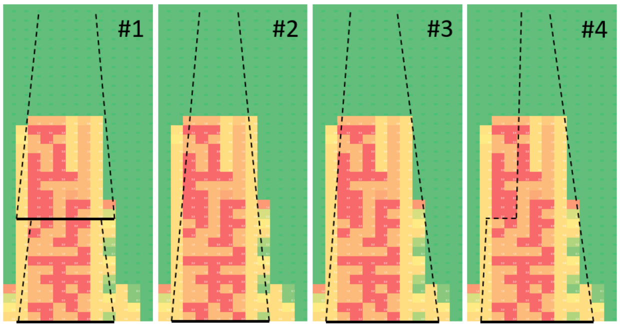


Figure 6 BC scenario trade-offs.

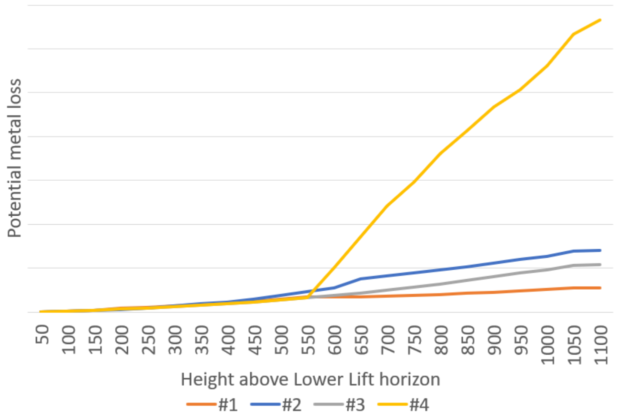


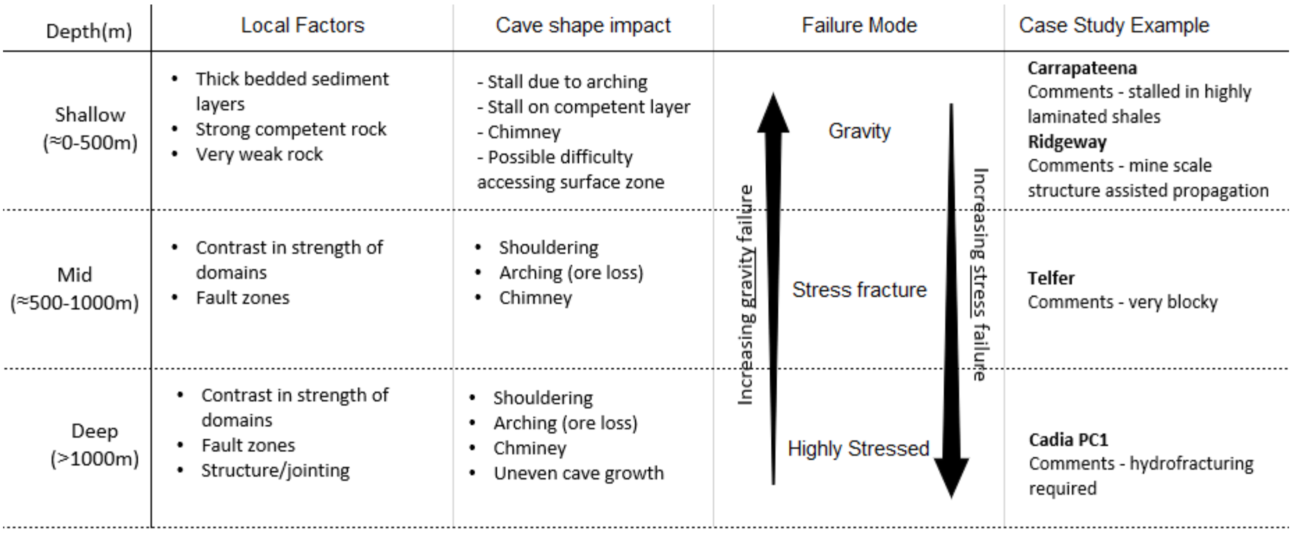
Figure 7 Relative comparison of BC scenarios.

The outcomes of the BC scenarios show the materiality of large scale underbreak with a ≈13% delta in metal recovery between scenario 1 and 4. This gives a relative estimate of potential impacts caused by potential geological heterogeneity impacting on cave shape. While this material may not necessarily sterilised, it does change the relative outcome of the initial BC. Trade-off of the other scenarios 1-3 have minor impact on the outcome in comparison although a sensitivity testing a range of cave break angles may be another useful consideration. In lieu of extensive drilling to confirm the presence of these conditions, the former plan with a wider footprint may be the more geotechnically robust 'base case' to account for expected but undefined heterogeneity. This demonstrates how a simple conceptual assessment and feedback loop can link potential cave propagation hazards to mine plan outcomes and strategic decisions. These key strategic decisions should be the focus of data acquisition and ongoing assessment. It may be prudent to carry multiple mine geometries through different study phases whilst the appropriate lithological understanding is developed as an input to design methods to inform cavability.

4.4 Cave shape outcomes.

The cave back geometries experienced during propagation can have significant impacts on the subsequent propagation through to surface, which is key for the management of the air blast risk, continuation of production and recovery. Potential outcomes influenced by alternate cave shape geometry include fines entry, groundwater entry and potential ore loss (Beck, et al., 2011). These factors that may influence cave propagation for various depths as well as illustrations of potential outcomes are summarized in Figure 8 and Figure 9. These illustrations are suggested as complementary high-level assessments to compare potential cave shapes, with consideration of the local conditions to test inputs built into any empirical or numerical assessment.

This process and development of alternate cave shapes is aimed to assist engineers to think divergently and consider all possible outcomes for the given study phase and level of data maturity. (Thompson, 1993) describes this consideration within studies well "perhaps the most important requirement is that the person have imagination." The outputs may assist identification and justification of drilling and data collection activities to reduce the range of possible alternatives or magnitude of potential impact. This visualisation step may also assist with communication of the importance of cave propagation behaviour within the organisation.



Depth(m)	Local Factors	Cave shape impact	Failure Mode	Case Study Example
Shallow (≈0-500m)	• Thick bedded sediment layers • Strong competent rock • Very weak rock	- Stall due to arching - Stall on competent layer - Chimney - Possible difficulty accessing surface zone	Gravity	**Carrapateena** Comments - stalled in highly laminated shales **Ridgeway** Comments - mine scale structure assisted propagation
Mid (≈500-1000m)	• Contrast in strength of domains • Fault zones	• Shouldering • Arching (ore loss) • Chimney	Stress fracture	**Telfer** Comments - very blocky
Deep (>1000m)	• Contrast in strength of domains • Fault zones • Structure/jointing	• Shouldering • Arching (ore loss) • Chminey • Uneven cave growth	Highly Stressed	**Cadia PC1** Comments - hydrofracturing required

Figure 8 **Local factors impacting caves at various depths.**

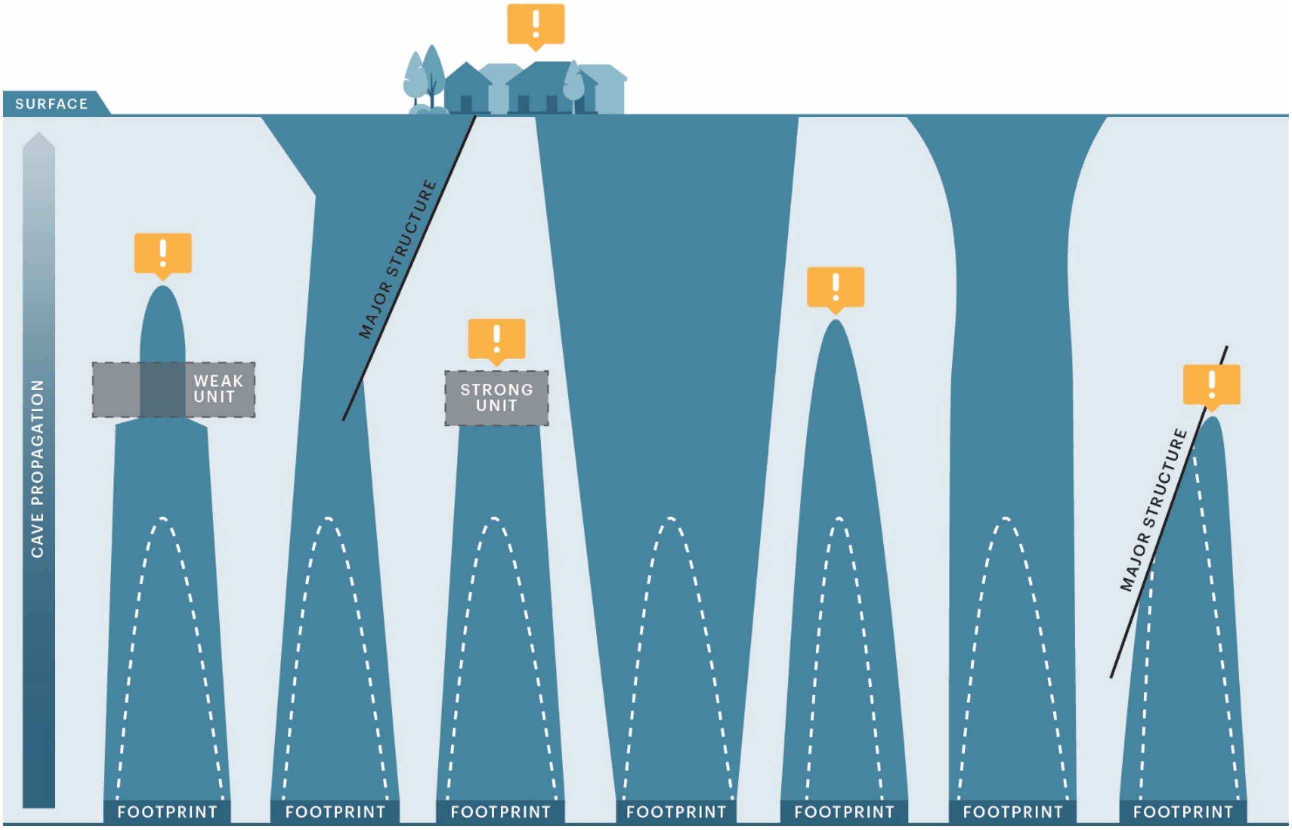


Figure 9 **Complementary high-level assessments to compare potential cave shapes.**

5 CONCLUSIONS

Deeper orebodies present additional challenges for cave propagation assessment with large volumes of cave column to characterise, plus challenging and time-consuming drilling programs. Despite technological advances in pre-conditioning, monitoring, and numerical modelling, cave propagation remains a complex process to accurately predict. In the absence of extensive data this behaviour is near impossible to assess with certainty; yet is generally defined by a single outcome. This paper challenges the reader to:

- Appreciate the complexity in cave propagation assessment and behaviour,
- Understand the limitations of data and assessment methodologies,
- Consider the potential unknowns within the orebody,
- Pose scenarios of potential outcomes,

Include appropriate contingency in the plan to reflect data maturity,

- Develop strategies that can be used to overcome potential threats, and
- Gather data to determine if potential threats are in fact present.

Having these scenarios imagined enables an engineer to develop targeted data collection, a range of potential geometries, and rock mass conditioning to set-up for the safe and optimised extraction of the ore deposit.

Deep cave mines may present increased risk, but also great opportunities. Cave propagation is not just about the initial and the final states. It is about the journey.

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