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Issues with transitioning from open pits to underground caving mines

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Abstract

This paper covers the issues and trends associated with transitioning from an open pit operation to an underground caving mine. The decisions made on the timing of the transition affect many parameters including the Mineral Resources (Resources) and Ore Reserves (Reserves), the timing and costs associated with the studies required to support the change. Fundamental issues such as the size of the underground operation and the anticipated ramp-up are discussed as well as the options afforded by Hybrid Caves (a Sub-Level Cave (SLC) later converting to a Block or Panel Cave (BC, PC)). The economics and risks of these strategies are discussed as well as the resultant impacts on traditional financial metrics. The authors believe that an holistic approach to evaluating the transition from open pit to underground is required, not simply an open pit optimisation, followed by a transition to an underground mine. Operations generally do not allow sufficient time, or plan the pre-requisite drilling programmes early enough, to make properly informed decisions about the transition.

1 Introduction

Most operations/companies struggle with determining the most appropriate time to convert from an open pit to an underground mining approach. This has been the subject of much discussion, especially in the MassMin series of conferences. Stacey & Terbrugge (2000) alerted readers to the fact that it may take 20 years to plan a transition from pit to underground in a large mining venture. A whole chapter was dedicated to the topic in Santiago in 2004. Most publications focus on technical designs with little reference to time scales or financial implications.

Typical optimisation processes for transition were described by Whittle et al. (2016) and this highlights some of the differences in current practices. The focus is on the optimisation process itself but does not give much guidance regarding what assumptions are appropriate for putting into the evaluation.

Fuentes (2004) makes the observation that open pit management are often in denial regarding what the optimum transition point is and convince themselves that there is still plenty of time. In the introduction to the chapter on transition from pit to underground mining in The AusIMM Guide to Good Practice, Ross (2014) makes the following statement:

"Most investment decisions are made on the basis of maximum net present value (NPV) for the starter pit. A series of pushbacks or phases are then planned to extend the pit life before serious consideration is given to the potential of any underground mining options. This sequence of decisions is understandable since capital costs are normally incremental for a pushback whereas most underground options will require significant upfront capital investment".

Unfortunately, the authors of this paper have seen many instances where the decision to evaluate the transition to underground is taken too late. Examples can be found in different commodities (e.g. diamonds, copper, gold and Iron ore) in different parts of the world (Africa, America, Australia). Why does this keep happening in the industry and what are the issues?

2 Issues and effects of procrastination

As stated in the introduction, the typical trend appears to be that serious consideration is not normally given to the underground studies until it is apparent that the next pushback in the pit is in doubt. Until this point, most open pit mine operators feel that they would rather accept the risks that they are familiar with, rather than seriously considering (underground specific) risks that they are less familiar with. As pits get deeper, they are certainly stretching the limitations of stability modelling. Are the models based on older lower highwalls truly representative of some of the massive pits seen today?

Bingham Canyon may be an example of unintended risk acceptance. After about 100 years of open pit operation, the decision to go underground was deferred once the South Wall pushback (open pit extension) was approved with a $1B price-tag. However, the Manefay failure in April 2012 was a significant event where 144 Mt of rock failed into the pit (Figure 1, after Ross (2016). Fortunately, no persons were injured as the pit had been monitored and evacuated ahead of the failure, but the speed of the failure and extent of resulting damage was surprising (Ross 2016).

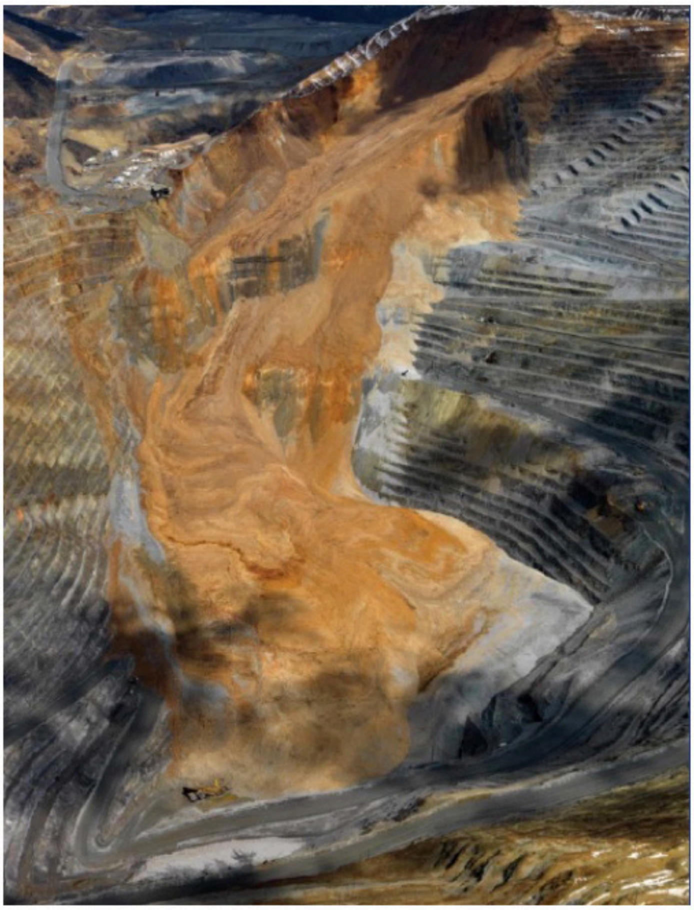

Figure 1 Manefay failure at Bingham Canyon

This failure stopped the pit from producing for several months (a gap in production) and the cost of rectification was not insignificant. It was recently announced that another Southern Pushback has also been approved for $1.5B (Mining Journal 2019). These two pushbacks ($2.5B) would have been comparable to the cost of a block cave mine development. An underground option would not have incurred the Manefay rectification costs. What would have been the decision if the Manefay failure had been anticipated at the time of comparing surface and underground options back in the mid-2000s? It certainly would not have appeared in any financial analysis, even if it did feature in a risk assessment.

Open pit operators generally tend to underestimate how long it takes to build an underground mine. Very few consider the amount of data collection, or the timeframe for drilling, data gathering, analysis and interpretation that is needed to perform reasonable conceptual, pre-feasibility (PFS) and feasibility studies (FS).

It appears that the typical strategy adopted is to plan to mine the pit to the maximum economic shell. Then the open pit management teamwork back from the end-of-life of the pit, basing the timetable for the transition from there. Often durations are assumed as per Table 1:

Table 1 Examples of typical assumed study durations

Level of study	Typical planned duration
Conceptual	6 months to 1 year
Pre-Feasibility	18 months to 2 years
Feasibility	6 months to 2 years

Are these timeframes adequate if all the drilling requirements are included? Probably not. Ross & DeWolfe (2016) discuss the timeframes for pre-production development of 10 to 14 years for large caving operations.

Is estimating the start of studies back from the planned final pit the appropriate option to enable the best result possible from the orebody? The real answer is probably complicated by many factors, both internal and external to the company.

Complicated or not, the trend is to leave the start of serious study work too late.

2.1 Resource drilling

In new mining ventures, open pits are normally the first phase of mining production activity. Once exploration drilling has identified the target and the follow-up programmes have been drilled to satisfy the requirements for concept and the various study levels, the pit can commence without serious interruption.

There will be opportunities to drill around the starter pit to improve the confidence in the surrounding area to allow the opportunity to expand the Resource base. The siting of major infrastructure may be a bit of a gamble, although a well drilled region will have sufficient sterilisation drilling done to allow processing plant, tailings facilities, utilities and waste dumps to be sited efficiently.

However, when an underground extension of the mine is being considered, a common issue is insufficient Resource drilling to justify the concept of going underground.

Once the pit is in production, it is very difficult to get an extensive resource drilling programme under way. Day to day production pressures discourage interruptions to operations. If holes must be drilled from outside of the pit area, hole lengths increase, and orebody intersection angles can become problematic (Figure 2).

In this (Figure 2) case angles are steep because of the location of infrastructure, process plant, tailings dam, and waste dumps. This makes orebody definition drilling difficult. The blue holes are planned to pierce the contact, while the orange holes are planned to be in ore for grade and geotechnical purposes. To step out beyond the infrastructure would mean a significant increase in hole lengths with resultant cost and schedule implications.

When drilling costs and timetables start to blow out, this places pressure on the studies and the subsequent decision making. There are examples of projects where the team made assumptions and hoped to verify the assumptions later in the study process. This can be a high-risk strategy. There are occasions when nature does not comply with expectations (e.g. faults do not follow projections) and this can necessitate changes to project execution strategy. This can add further cost and schedule pressures.

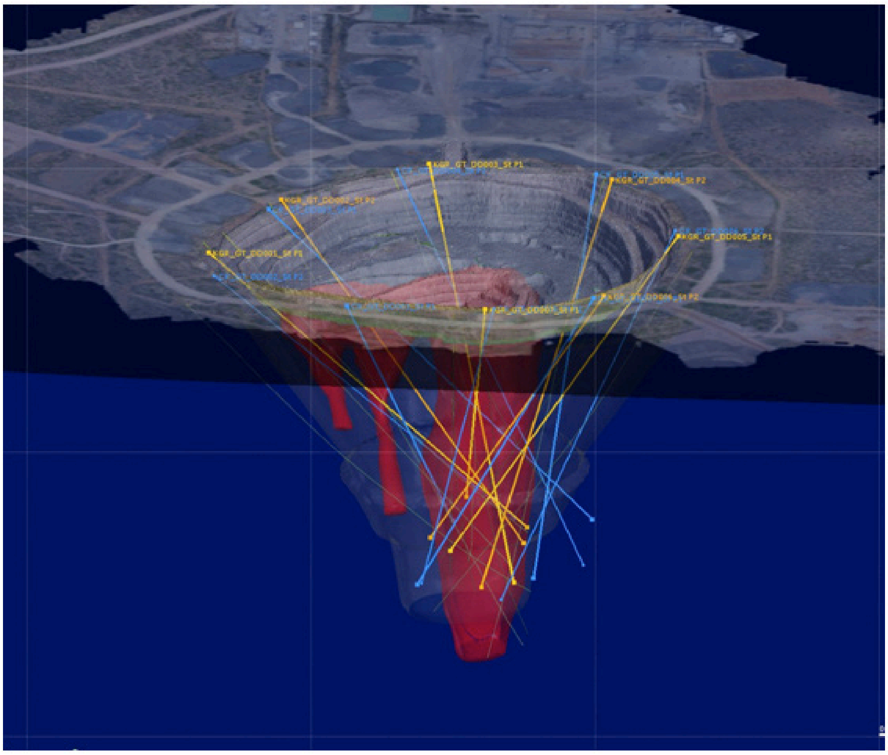

Figure 2 Open pit and planned drill holes

2.2 Geotechnical information

Historically, geologists ran geological drilling programmes focussed on obtaining core and mineral samples. Their focus was to develop a geological interpretation of structure (and develop a model) and evaluate the mineral Resource. The bulk of the drilling focussed on "adding value" by increasing the size or grade of the Resource (or both).

The requirements of geotechnical engineers were not normally considered and often required drilling of specific holes to obtain the required geotechnical information and samples for strength testing etc. With improved technology, much more data can now be collected from drill holes and this makes sense from a cost perspective. An unfortunate downside is that the collecting of additional data often "slows" the drilling programme as the drill rigs are generally required to remain at the hole to allow the equipment to be raised and lowered in the hole.

If the timing of the drilling programme is on the critical path for the project, it is likely that pressure will be applied to "speed things up". This may be possible by the application of more resources, which come at a cost. As stated by Morrison (2017), in projects when faced with the choices between quality, time and cost, you can never get all three – something will suffer.

2.3 Risk

The importance of collecting quality structural information when investigating the transition from open pit to underground should not be underestimated. Examples of open pit instability resulting from the interaction of caving mines migrating up into existing open pits include Palabora (BC), Earnest Henry (SLC) and Perseverance (SLC). At Earnest Henry, the SLC step out on an inclined orebody led to open pit instability, with subsequent large-scale failure of the existing, previously mined open pit (Campbell et al. 2016). The well documented case of pit wall instability at Palabora (Severin et al. 2010; Sainsbury et al. 2016) led to a +100Mt failure that had implications for both the cave and the infrastructure beyond the pit limits. The Reserve at Palabora was reduced by 50Mt and additional 9Mt of dilution was included in 2005 (Ross 2014). At Perseverance, subsidence related to SLC impacted on the previously mined open pit and then broke back beyond the pit limits to threaten infrastructure, in this case a ventilation shaft (Tyler et al. 2004).

The role of geological structure is also important for evaluating the rate of cave progression in general, as outlined by Dunstan (2016) for the Ridgeway SLC mine and Lett et al (2016) for the Cadia East PC1 breakthrough to surface. The importance of structures to the cave surface subsidence footprint is emphasized by many authors, as highlighted by Vyazmensky et al. (2008). Flores & Catalan (2019) discuss the importance of structure and mitigation strategies to prevent dilution from the large West Fault in the Chuquicamata Open pit. Wellman et al. (2008) discuss the analysis of potential pit slope stability issues for the Grasberg Open pit to underground transition.

2.4 Modelling

Many drill programmes focus on Resource drilling within the orebody. The business case for this expenditure is normally straightforward. More drilling allows greater confidence in the geology and grade and the payback is generally increased Mineral Resources which can justify additional capital spend to convert to Ore Reserves. How much drilling is done to understand the properties of the host rock surrounding the orebody? This drilling would be purely for geotechnical reasons and should inform the mining study. If these holes are left until last, the results are all too often too late to be included in the stage of study in which they are drilled.

The development of the geological and geotechnical models can only be completed after all the information has been gathered and processed. All too often, schedules do not allow enough time for thinking and interpretation. Van As (2014) makes the point that the collection of geotechnical data is a slow and thankless task. More importantly he notes that:

“A well characterised rock mass forms the basis of all subsequent data analyses from which the rock mass behaviour in response to mining is predicted, thus ensuring that optimal mine designs can be developed.”

If the geotechnical drilling programme is rushed or pared back, this could provide a very weak foundation for subsequent design work.

The application of experience and judgement is not necessarily instantaneous as there are no Apps for that. This may change in the future with the use of “Big Data” and Artificial Intelligence.

3 Studies and options

Conceptual Study followed by a Pre-Feasibility Study (PFS) leading to a Feasibility Study (FS) is a fairly typical concept of how a mining project progresses. However, there are widely ranging views on what each study level requires.

An approach by Dyas (2002) suggests that a conceptual study is a preliminary evaluation of a project but goes on to say that drilling and sampling must be sufficient to define a Resource adequately. He maintains that this level of study is useful for defining required inputs and studies but not appropriate for decision making.

Further he asserts that a PFS is an intermediate step between conceptual and FS where cost estimates are +/- 30% but not sufficiently accurate for decision making.

He sees the FS as a 'bankable document' and suitable for "go" decisions and financing purposes and cost estimates are +/-20% or better.

Companies differ in their definitions but generally have approaches that are just variations on a theme. Some have the study progression as conceptual to PFS "A", PFS 'B", FS. Another organisation has Scoping followed by PFS followed by FS leading into detailed engineering. There are a host of terms used to describe variations on the FS, e.g. Definitive, Bankable and more.

The components of each stage of study can be variable in quality and accuracy. This may be a reflection of the skills and preferences of the study team, or the availability of data. It is not uncommon for, say, the mine design to be of FS quality, but the engineering and services work may only be of PFS accuracy.

However, if the Resource and geotechnical information is not complete, all the subsequent work is of questionable value.

3.1 Conceptual study

This stage of study does not require extensive detailed orebody knowledge following an extensive drill campaign; however, it does set the scene for management expectations. Things such as targeted levels of production and potential mining methods are normally discussed (or established) at this early stage. If there is at least one option that potentially makes money, the next phase of study can normally be justified.

The resulting level of accuracy of these studies are vague. Some may claim +/-40%. This is probably generous given the lack of detail.

3.1.1 Tonnage and scale of underground conceptual mine

This is a fundamental issue and a key driver of capital requirements, but how is it determined? Unfortunately, some studies are given "the number" before the underpinning work has been done. It can be a case of simply "fill the mill" that is already there. This is not the recommended route but one that is often observed. It is never easy trying to replace an open pit with an underground mine on a tonne for tonne basis. Ross & DeWolfe (2016) discuss the relationship of pre-production development requirements, as well as the role that column height plays in supporting a production rate.

Ultimately the scale of an underground operation is a function of the orebody and the "Four G's":

1. Geology (complexity, faulting, continuity)
2. Geotechnical properties (rock strengths, stresses, stability)
3. Geometry (size and shape, regularity)
4. Grade (overall grade, distribution, zoning or trends)

These are physical constraints and are the real factors that determine a mine's production potential. Some will argue and make a case for altering the rock strength or shifting the stress field by "pre-conditioning". This can be done, but it comes with a price tag and a time requirement. The costs and schedule required will still be a function of the in-situ geotechnical properties.

There will also be other constraints to be considered such as availability of capital, existing infrastructure capacity, workforce and culture, regulatory limitations and environmental permit conditions. These are "administrative" constraints. They can all be modified but will also require time and resources to change them.

If the process of identifying constraints and generating strategies to eliminate or modify them is not started early enough, they can ultimately delay a project (or become a fatal flaw).

3.1.2 Continuity of production

In most cases where a transition is considered from an open pit to underground operation, there is a stated intent at this stage to have a "seamless" transition in terms of production. Any "production gap" invariably damages the business case. Whilst at the conceptual level, a high-level view is often that the pit can produce and even stockpile ore (even if at a lower grade) to maintain production through the transition period.

This is carried into the next phase of study, where the issues begin to appear.

3.1.3 Setting expectations

While at the conceptual stage, it is often assumed that the readily identifiable problems will be sorted out during the study phase. This is quite reasonable, assuming sufficient time is allowed for the solutions to be developed and implemented. Smaller organisations, with low levels of bureaucracy, can be quite nimble and often underestimate the time required to change the views of regulators or obtain the prerequisite approvals before critical activities must be commenced. Governmental departments are not renowned for flexibility and rapid responses.

Once the global numbers of output, grade and indicative values are tabled in a conceptual study, it is very difficult to "retreat" to lower levels of production or significant reductions in NPV. Management expectations have now been set and project teams feel obliged to deliver a more detailed study that maintains value.

3.2 Pre-feasibility

This is often where many studies/projects fail to meet the original intentions of the conceptual study. As more work is done to an improved level of detail, additional issues that were not considered in the conceptual study start to appear.

As mentioned above, many organisations aim for a confidence level of +-30% on a PFS. Some split the study in two parts (PFS A and PFS B), others are less formal.

3.2.1 Mining options

It is generally the intention that the PFS should explore all the potential options. Unfortunately, the time and budget available is often insufficient to allow that to happen. As indicated in section 2, the Resource (and geotechnical) drilling is often incomplete. The normal state of play is that not all the holes drilled under the PFS budget have been completed. If they have been, the information is consolidated too late to be included in the PFS report. It is quite unusual for the PFS to have the Resource drilling of an underground mine completed prior to commencement of the study. This invariably means that not all options can be properly explored without making some assumptions.

When time is limited, perhaps striving to make findings known prior to a board meeting, and not all options have been explored, study teams make choices or decisions. Normal practice would be to select one or two alternatives for further work and preferentially discard the least likely options. Unfortunately, this step often occurs before all the drilling results are available. This is where opportunities can be lost.

3.2.2 Tonnage and scale

Studies tend to aim for the target tonnage outputs stated in the Concept study or improve on them. This is logical since management expectations have already been set and the study team sees that as their function. An example noted by Wellman et al. (2012) was that the Grasberg Block Cave was conceptually planned at 50 ktpd, and by 2003 was studied in Pre-Feasibility at 110 ktpd. At the end of the Feasibility analysis this had increased to 160 ktpd.

3.2.2.1 Staged development

A discussion is warranted on the consideration given to "staged" project development. There is often a smaller, high value project lurking within a larger one. This could be as straightforward as a high-grade starter cave, preceding a larger panel cave. Other options may be a high-grade sub-level stoping operation (or even an SLC), selectively mining a high-grade zone before establishing a larger operation suited to the long-term planned production tonnage profile.

A staged option may not provide sufficient tonnage to meet the expectation of a "no-production gap" transition from open pit to underground. At the end of the day, the discussion should be about value, and what is best for the business, not an arbitrary tonnage number.

There are some downsides to considering options that produce lower tonnages or designs that are more selective. One that is rarely anticipated is that differing scales of production require different drill hole spacing to conform to norms for Measured, Indicated and Inferred Mineral Resources. Smaller daily tonnes require more closely spaced drilling to ensure similar confidence levels. If these have not been considered early enough, it is unlikely that enough drilling will have been done to support the generation of an official Reserve.

This is often an aim of a PFS, which may be required to be able to attract or justify significant capital for the project to proceed.

"Modular" u/g expansions have also been considered in some large-scale caving projects (e.g. Chuquicamata, Figure 3 and Resolution, Figure 4).

Figure 3 Chuquicamata macro blocks on 1,841 Lift (after Aguayo et al. 2012)

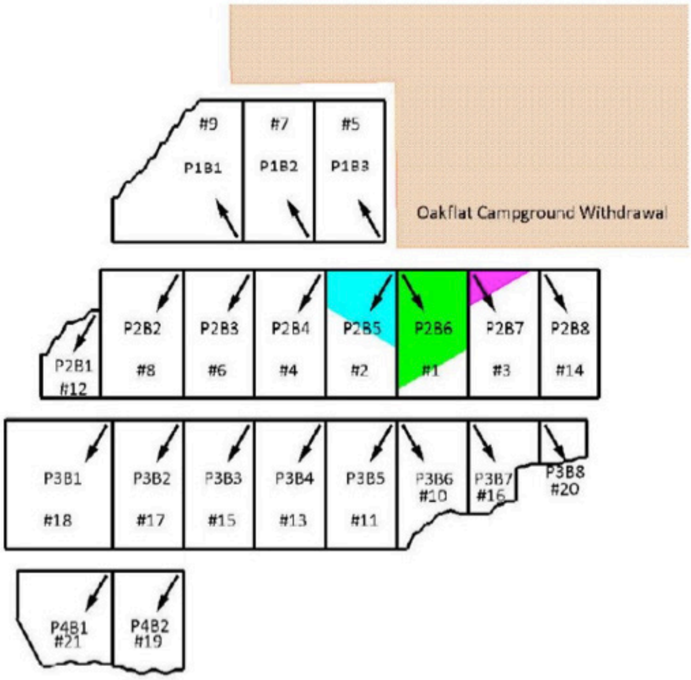

Figure 4 Resolution - possible mining sequencing micro-panels (after Gantamur et al. 2016)

3.2.2.2 Hybrid options

After looking through several PFS reports, it is surprising to see some mining methods discarded at an early stage, even though some of the benefits are recognised. It should be remembered that often, one size (or method) does not fit all situations, or even different parts of the same orebody.

More recently there appears to be more focus on the possibilities of "hybrid options". An example of this might be to employ a SLC initially, until a Block Cave (BC) or Panel Cave (PC) can be established at a lower level. This is the strategy being employed a Carrapateena, even though the deposit was never mined as an open pit. Another example is with Debswana as they consider options for future underground operations at both Jwaneng and Orapa.

Operations that have a final pit design that drives down on to a relatively small high-grade core will typically leave mineralised material in the walls of the pit that cannot cover their incremental stripping costs. This material might be readily accessible should a decline be planned to access the underground mine below the pit.

Figure 5 illustrates the point that such a pit may get benefit from employing different mining methods at different stages of production. Examples of mining methods include:

1. Sub Level Retreat Mining (less early dilution)
2. Sub Level Caving (earlier, "top-down" production)
3. Block Caving (long period of undiluted, low wet muck risk production period)
4. Assisted Caving (Vertical Crater Retreat (VCR)) – (for narrow areas that will not naturally cave)

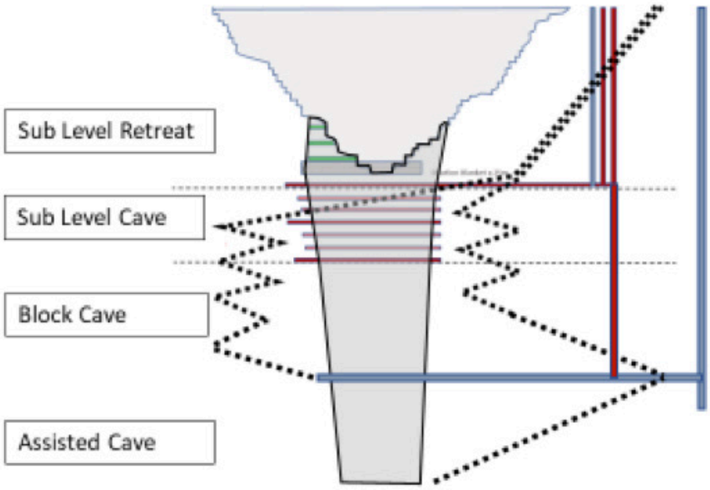

Figure 5 Schematic hybrid transition

There are always modifications and adaptions that can be made to enhance value. However, they take time to consider and evaluate properly. If the basic Resource data is late or there are gaps impacting on more selective options, these opportunities may be lost. Dilution modelling cannot be reliable without some estimation of how fragmentation and slope failure may occur.

3.2.3 Production continuity

Once some mining options have been developed and basic schedules applied to their establishment, then the true picture of the issues around continuity can be seen. If, as is typical, the studies have been too late in commencing, and all the Resource information is still being gathered, there will probably be a production gap.

The project team will then be obliged to see what can be done to limit the damage. This can be where projects get themselves into trouble. The obvious levers for closing the production gap is to accelerate development and the production ramp-up. Some projects may acknowledge there is an issue and assume that during the Feasibility Study, they will have the opportunity to minimise the issue. In the authors experience, the opposite tends to happen, and the gap gets bigger.

3.2.4 Ventilation

This is one area that, in many studies, is not given sufficient thought during the PFS. In a transition from an open pit, the ventilation planning can be significantly affected by existing infrastructure. It can be quite problematic trying to identify suitable positions for ventilation shafts to support the underground access development as well as the final mine design.

Items such as waste dumps close to the pit, break-back angles from deep seated caving options, siting of tailings dams, process plants and offices can result in infrastructure being located much further from the accesses and designed workings than would be on a greenfield underground only design.

This in turn puts further pressure on the schedules if build up in both development rates and production rates are constrained by a lack of available ventilation. It is yet another reason to get the studies underway in plenty of time to cater for the unanticipated.

3.2.5 Pre-feasibility study outputs

The outputs from the PFS are normally:

- A recommendation for two alternatives to be explored in more detail in the FS;
- A summary of key issues to be concluded in the FS; and
- Sufficient justification to declare an update in Resources and a Reserves.

3.3 Feasibility

Feasibility is where the detail gets hammered out. The aim is to get more accurate detail on designs, costs and schedules to get the estimates within 20% (although some claim 10%). In reality, this would be the exception. Many projects try and roll straight from PFS into FS and see it as a process, simply to fine tune more detail on the preferred option.

More detailed work is completed, but the devil is in the detail. If the drilling programmes (and subsequent data gathering and analysis) are delivered late, detailed work on questionable foundations will not deliver an accurate result.

If the project studies have been on a tight timeframe due to production pressures, the completion of the FS may just be a rush to get something approved before the pit finishes. This should be the work that leads to the best way forward for the business.

3.3.1 Mining options

There are traditionally two options, at most, to work through during the FS, and often only the one, which requires more detail. However, if some of the suggestions above are implemented more regularly, the options may get more complicated as different mining methods for different scenarios require more detailed evaluation.

Examples may be:

- How many benches (or levels) are taken?
- Which orientation?
- How deep does the SLC go?
- What is the optimum height of draw for a BC/PC given the preceding analyses?
- When are the various ground handling systems available?

3.3.2 Tonnage and scale

Given the work performed during PFS, there are not generally big surprises when it comes to the FS as far as tonnage and scale are concerned. There are always exceptions. As mentioned in section 3.2.2, Grasberg Block cave jumped from 110 ktpd to 160 ktpd during the FS analysis. Increases of this order of magnitude are rare though.

Where the output is likely to be constrained through infrastructure, tonnage is not likely to increase significantly. It is generally not realistic to expect an underground operation to replace a fully functioning open pit on a tonne for tonne basis. If for no other reason, the cut-off for the underground mine is higher than the open pit on the same orebody, leading to a reduced volume available for exploitation.

Both the staged development and the hybrid mining methods present the same issues under tonnage and scale insofar as there are multiple pathways to achieving the total daily tonnage. They are different means to the same end, i.e. the pathways to the final planned level of output. However, the staged development or use of different methods for different areas will undoubtedly have an impact on the production "gap".

3.3.3 Continuity of production

This is probably the most contentious area of the study for the study team and mine management. The implications of the size and duration of the production gap are both significant and far-reaching. The obvious implication is the drop in production (revenue) and the fixed or period costs, both affecting cash flow. Without the open pit to carry the overhead costs, must they be carried by the underground project? What are the options? Unpalatable options to consider include:

- Retrench all personnel not part of the project (admin, processing, maintenance, etc);
- Reduce salaries;
- Force employees to take leave; or
- Suspend service contracts.

None of these options are likely to have full support from the existing workforce or the community. Also, should current skilled employees be "let go", what are the prospects of getting them to return when the transition is complete? Probably not good. The more highly skilled and valued employees will find it easier to find alternative employment than the rest.

Even if relocation is offered to (for example) open pit truck drivers to future underground roles, the percentage take up is traditionally low. Most are not very interested until the reality of pit closure is imminent. Then it is too late for retraining as vacancies should have been filled during underground development and ramp-up.

3.3.4 Feasibility outcomes

Sometimes "NO" is the right answer (e.g. Argyle) but most project teams would see that as a "failure".

Project teams have been determined to make a "success" of the PFS/FS by rising to the challenge of "closing the gap". They may have tried strategies such as:

- Accelerated development rates;
- Juggling development resources to maximise productivity;
- Ignoring "inconvenient truths" about ventilation availability (or omitting the time it takes to install ventilation controls to effect circuit changes); and
- Aggressive ramp-ups:
    - Optimistic undercutting rates;
    - Rapid drawpoint installation; and
    - High rates of early draw.

Mining is recognised as being a "risky business". The industry has made tremendous advances in the last 20 years to improve its performance in safety (although perhaps not succeeded on fatalities) but few projects live up to the initial promises released to the market. One recent example is the cost increase and delayed production at Oyu Tolgoi announced by Rio Tinto in 2019. Fitzgerald (2019) reported that the $5.3B underground expansion was looking at a:

"$1.2-1.9 billion cost blowout in the underground development, and the 16-30 month delay to May 2022-June 2023 to reaching steady state production of more than 500,000tpa".

This reinforces scepticism and ultimately increases the cost of capital as lenders want more security. It is incumbent on those who are responsible for the long-term future of mining operations (Boards and senior management) to provide ample opportunity for studies to be done properly. That includes the time and funding for appropriate drilling and data gathering programmes to be completed to support the various levels of study. It is irresponsible to expect accurate studies to be performed with inadequate time, information and resources.

A robust plan for a transition from a pit to underground mine with a strong financial justification are the ideal outcomes from a FS. But what are the most appropriate metrics to use? NPV can drive projects to seek the lowest capital cost option and accept higher operating cost levels as a result.

4 Economic and financial implications

4.1 The transition

A large number of authors have attempted to solve the transition point from open pit to an underground mine. This transition problem is well summarised in papers by Chung et al. (2016) and Whittle et al. (2016). Most of these approaches focus on breakeven cashflow (generally undiscounted) or profit as the objective and seek to optimise the tipping point, with or without a crown pillar. None of these methods addresses optimisation in terms of potential underground cut-offs or production rates and have not incorporated different underground mining methods (either standalone or in combination).

The combined optimisation approach of Whittle et al. (2016) when selecting the transition from open pit to underground, typically generates smaller pits than optimising only for an open pit. This alone informs us that planning for the transition should commence earlier then is suggested by evaluating the optimum pit. It is the experience of the authors that open pit pushbacks are selected with the final pit as the end game. Little consideration is given to the incremental value or stripping requirements of the last and next to last pushbacks, either as a standalone proposition or in relation to selecting the transition to underground. In the largest underground mass mining deposits transitioning from open pit (e.g. Chuquicamata, Grasberg), the planning has been decades in the making and the decision has been to mine using bottom up caving methods.

4.2 Mining method and economics

The trade-off between the earlier revenue generation associated with a top down mining method such as SLC needs to be compared with either mining the same region of the orebody as a potential Block Cave (bottom up), or mining the adjacent lower grade material as a Block Cave and lower portions of the orebody via block cave. Two examples from Australia have gone down this path. The Ridgeway ore body in NSW was initially mined as an SLC due to early access to high grade portions of the orebody and to generate revenue as early as possible. Deeper portions of the orebody were subsequently mined using Block Caving (Manca & Dustan 2008; Dunstan 2016). The Carrapateena orebody in South Australia is another example where an early SLC option is commencing mining, with studies progressing towards the mining of both the adjacent lower grade material utilizing Block Caving (OZ Minerals 2019b) along with deeper portions of the orebody (OZ Minerals 2019a).

Transitioning from the open pit to underground using top down cases, bringing forward the revenue potentially has the benefit of minimising the Maximum Cumulative Negative Cash Flow (MCNCF). This is demonstrated conceptually in Figure 6, where the cumulative cash flow and revenue are graphed for the first 12 periods (corresponding to the payback period) of a Block Cave only project compared to a project that has a transitional underground mining method (SLR/SLC) mined in the period leading up to the commencement of the Block Cave. The difference in MCNCF in period 7 represents approximately $0.7b in capital that would not be required due in part to the revenue generated in periods 4-7. This is important as the ability to fund the project from earlier revenue streams generated by the top down mining methods reduces the call on capital required at the front end of the project. Access to funding for such large projects is another risk factor that is often overlooked in Feasibility studies (Stewart & Butcher 2016).

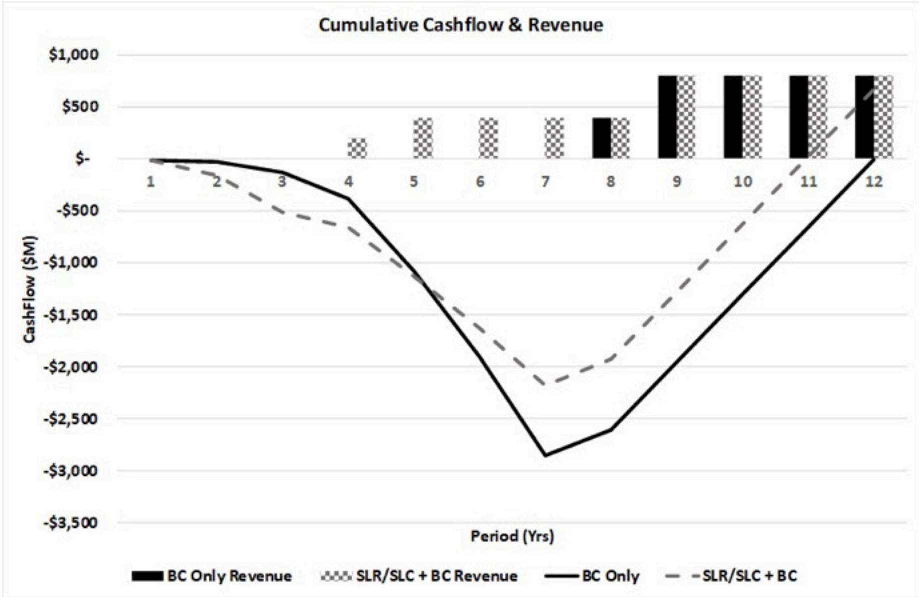

Figure 6 Maximum cumulative negative cashflow concept - Graph of cumulative cashflow and revenue

There are several examples going back over 80 years where top down mining methods have been used at the base of open pits. The Cullinan mine in South Africa started underground mining in 1947 following open pit mining with Sub-Level Open Benching (SLB) mining, followed progressively by Block Caving using scrapers and finally mechanised Block Caving through to current times (Tukker et al. 2016). The Finsch mine in South Africa transitioned to underground from an open pit, with two Blocks of Sub-Level Open Stoping (Blocks 2 and 3), followed progressively by a Block cave (Block 4) and an SLC (Block 5) (Mining Technology 2019). Several of the open pits at Ekati and Diavik in Canada have transitioned underground using Sub-Level Open Benching and Sub-Level Retreat mining and Sub-Level Caving/Inclined Caving (Ekati Koala Orebody) (Jakubec et al. 2017; 2018).

4.3 Selecting the correct metric

Stewart & Butcher (2016) outline alternative financial metrics for selecting the optimal mass mining project. When considering the transition from open pit to underground, the evaluation utilising transitional mining methods will still require large capital outlay over significant time spans. The largest project that provides the best Net Present Value (NPV) is not necessarily the best project from a risk or economic perspective. Technical and commercial risk both increase with project size (McCarthy 2010). Transitional projects (top down methods) not only provide lower risk, smaller projects, but can also lead to higher Present Value Ratios (PVR, the ratio of NPV to the present value of the project capital) due to the delay in spending capital and the common capital shared between the transitional project and the larger caving project. PVR is used in economics when access to scarce capital means projects need to be ranked against other projects in a portfolio, or when options for the same project need to rank against each other. This can be achieved using Hill of value techniques (e.g. Stewart et al. 2010) to evaluate the optimal PVR, compared with optimizing for NPV. Hall (2014) notes that ranking options by PVR and selecting those with the highest PVR's will produce the highest NPV from the capital available.

Trade-offs between optimising for economic value and capital efficiency measures allow for decision makers to evaluate potentially higher risk, higher-capital and maximum NPV projects against lower-risk, lower-capital projects.

5 Conclusions

A prudent approach to transition from an open pit to underground mine should include:

- Start studies earlier to ensure a smoother transition;
- Commence resource and geotechnical drilling programmes as early as possible;
- Allocate sufficient time and resources to ensure the studies can deliver appropriate levels of accuracy;
- Look for opportunities to construct in phases (stages) and;
- Employ appropriate mining methods in the suitable areas.

Such an approach requires less up-front capital and puts less capital at risk until the technical challenges associated with a particular project are known and addressed. It then paves the way for future expansion. This will greatly reduce the risk of destroying shareholder value.

The authors believe that a holistic approach to evaluating the transition from open pit to underground is required, rather than just concentrating on the tipping point between the open pit and the underground mine.

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