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Deep Mass Mining White Paper

Deep Mass Mining

The Key to Sustaining Mineral Demand into the Future

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Executive Summary

Context: Deep Underground Mass Mining – The Only Option

The future of mining lies underground, and the future of underground mining resides predominantly in mass mining methods, as only these have the ability to yield the vast quantities of minerals required to meet the world's increasing demand. On the first instance the focus will be on porphyry copper deposits, which make up the bulk of known copper resources. Until more recently, mass mining methods have only been utilised to extract shallow- to intermediate-depth orebodies; however, the past two decades have seen mining companies push the envelope by applying these methods to much larger scale deposits at depths of around 1000m. Current planning / development for even larger mass mines at greater depths, which are accompanied by significant technical and operational challenges. These ultimately translate into unprecedented levels of mining risks which need to be identified and mitigated.

The Problem: Challenges with Deep Mass Mining

The resurgence in cave mining methods has been motivated by the fact that most of the large, easily accessible near surface deposits have been mined out (or cannot be mined for various reasons). The profitable extraction of ore from large open pits becomes increasingly more difficult with depth, not only due to the high strip ratios and logistical complexity, but also because of the expanding mining footprint and associated environment, social and governance (ESG) pressures.

Thus a substantial amount of future ore extraction will occur deep underground, though most of these deposits are anticipated to be low grade (e.g. average grade < 0.5% Cu) and their economic viability depends on extracting very large tonnages of ore at low cost. The technical successes of deep, high-column, cave mines have, so far, been mixed. Cave underperformance is typically ascribed to geotechnical factors that were either unidentified during mine feasibility studies or their impact was poorly predicted and mitigated. Ultimately, geotechnical factors have increasingly been blamed for construction and development schedule delays, mine instability, loss of reserves, higher dilution and higher costs, all of which erode project value and investor confidence.

There is however, considerable debate over whether these geotechnical factors are truly unpredictable or are rather:

- the inevitable outcome of poor data acquisition and inadequate data analysis that inform the geo-models which form the basis for mine design;
- the inadequate incorporation of geohazards / risks into mine planning and reserve recovery predictive models;
- induced through poor mine design and poor operational practices.

Qualification: Deep Mining Geoscience Research Group

In an effort to address the technical challenges and risks associated with deep mass mining methods, the WH Bryan Mining Geology Research Centre (BRC), within the Sustainable Minerals Institute at the University of Queensland, has formed a 'Deep Mining Geosciences' (DMG) group which is tasked with developing a strong industry-collaborative programme of applied mining research and education in the area of Deep Mining Geoscience. The DMG group enjoys ready access to world-class geoscientific and mass mining expertise and is led by Prof. Andre van As, a CSIRO medal recipient who has over 30 years of mass mining experience and sits on several cave mining technical review boards across the industry.

The Solution: Deep Mass Mining Research & Education

Recent meetings and workshops with technical personnel from several major mining companies have identified a range of technical issues that require urgent research attention. To this end, DMG research will focus on six key areas that encompass the majority of the issues identified by the mining industry and where coordinated collaboration and resources will facilitate the much-needed step change required for deep mass mining design and operations.

The 6 key areas cover:

1. **Geoscience Characterisation**: Address issues of geo-data acquisition, geo-data fusion that integrates multiple data sources, geo-data processing and interpretation, and the development of reliable geo-models that incorporate data variability and data uncertainty into the rock mass characterisation process. Reliable geo-models form the foundation of reliable mine design.
2. **Rock mass Conditioning**: Research the fundamental mechanisms of rock-mass (pre- and post-) conditioning technologies, and their effectiveness in managing geohazards and improving cave mine performance; particularly in deep high-stress mining environments.
3. **Deep Mass Mining Geo-Risk Management**: Research focused primarily on back-analysis of mine monitoring, reserve recovery, and production draw data from multiple cave mines in an effort to identify key drivers responsible for escalating geohazards in mass mines, and to subsequently develop key hazard indicators that will form the basis for developing mine-geohazard models. Geohazard models integrated with geotechnical monitoring systems and real-time operational (e.g., undercutting and production) databases, will be imperative for effective real-time geohazard management of deep mass mines.
4. **Material Flow in Deep Cave Mines**: Research the mechanisms of drawzone growth and drawzone interaction under high vertical loads (high cave columns), the results of which will be key to improving deep cave layout designs, and in developing draw strategies that effectively control cave propagation, reduce dilution, and manage vertical stress loading on the extraction level.
5. **Mining Method Design Improvements**: Research into new and modified mass mining methods and techniques that better suit deep underground mass mining, including reducing mining- induced surface effects.
6. **Education**: In addition to the above research, DMG will develop a postgraduate education programme in the form of (1) a mass mining Masters course (in collaboration with UQ's School of Mechanical & Mine Engineering) and (2) a mass mining professional development programme. Both of these will serve in addressing the existing skills shortage of mining professionals, particularly in underground mass mining.

The How: Resource Requirements

The success of any research group lies in the strength of its team and the commitment of its partners to ensure support, via funding, providing relevant data for research purposes, personnel, and involved collaboration. By formalising long-term partnerships, DMG will be well-placed to deliver both its above research objectives, and the educational/professional development objectives of its industry partners. It is, however, imperative that industry partners are more than just benefactors, they must be active participants. This can be achieved by nominating industry project champions and, ideally, seconding accomplished research candidates into DMG from industry partners.

The Value: Benefits to Industry

Given the anticipated large scale of future mass mines and the deep and harsh mining environments in which they will mostly be developed, it stands to reason those unforeseen geo-risks can have catastrophic consequences. At the very least they will translate into significant development and operating cost overruns; for example, it was reported (Reuters, August 9, 2021.), that due to weaker than expected ground conditions the Oyu Tolgoi project has been delayed by almost 2 years with cost overruns estimated at around $1.45bn. Similar several large, mining induced, seismic events have occurred at various operations, which have resulted in significant damage to underground excavations (requiring expensive rehabilitation), as well as substantial production losses and mine development delays.

Simply put, the mining industry can no longer afford to continue to 'cut and paste' mine-designs that were developed for a completely different mining environment. Applying past state-of-the-art, empirical relations that stretch beyond the supporting data introduces an unacceptable level of risk into mine design, which could continue to cost the industry billions of dollars in losses and ultimately attract the attention of regulatory authorities and in some cases increase sovereign risk. An example of this issue is exemplified by recent correspondence from the Australian Securities and Investment Commission (ASIC) to the Australasian Joint Ore Reserves Committee (JORC), expressing concerns "*with respect to competence relating to some recent high-profile mining developments that materially under-performed and resulted in significant shareholder loss. Further concerns were expressed around the efficacy of competence self-nomination. Specific concerns were also raised around Competent Person(s) taking responsibility in Public Reports for broad technical areas that are likely well outside their relevant experience. It is clear from the ASIC correspondence that there is no 'do nothing' option with respect to the issue of competence in reporting*", (AusIMM news, Update on the Competent Person issue in the current JORC Code review, January 2022).

New and/or modified mass mining methods, tailored to optimise the extraction of ore reserves and to minimise the effects of geohazards will avert billions of dollars in unforeseen losses to mining companies and society, and enable the mining industry to secure the mineral/metal production to meet the future demand

1. Context

1.1 Future Mineral Resources

1.1.1 Copper Availability

There is considerable debate over the quantities of copper currently available for mining. Singer (2017) optimistically estimates that there are around 2,030 million tonnes available from known deposits and estimates a further 4,350 million tonnes from undiscovered deposits; totalling 6,380 million tonnes. Others are of the opinion that the contribution of undiscovered deposits will be small (Kerr, 2014), as they argue that most known deposits have already been discovered and thus copper will be critically scarce by the end of the century (Gordon et al, 2006). However, similar dire claims could have been made in times past and were; but were subsequently demonstrated to be grossly incorrect. Wood and Hedenquist (2019), and others predict that future ore deposit discoveries will be made in similar numbers as in the past; but at depths beginning deeper than the 200 m limit to the top of ore below surface that typically precludes mining by open pit.

Adding to the complexity of the debate is the fact that Environmental, Social and Governance (ESG) and climate change factors may dictate the availability and costs of all future mines (Gordon et al, 2007); with many future deposits being labelled as 'unmineable' regardless of any rise in the copper price, (Valenta et al, 2021).

Thus, regardless of the availability of copper deposits, one thing is certain, namely that many future copper mines will be developed in deep, complex, low-grade, massive orebodies, that can only be mined by a mass underground mining method, as illustrated in Figure 1.

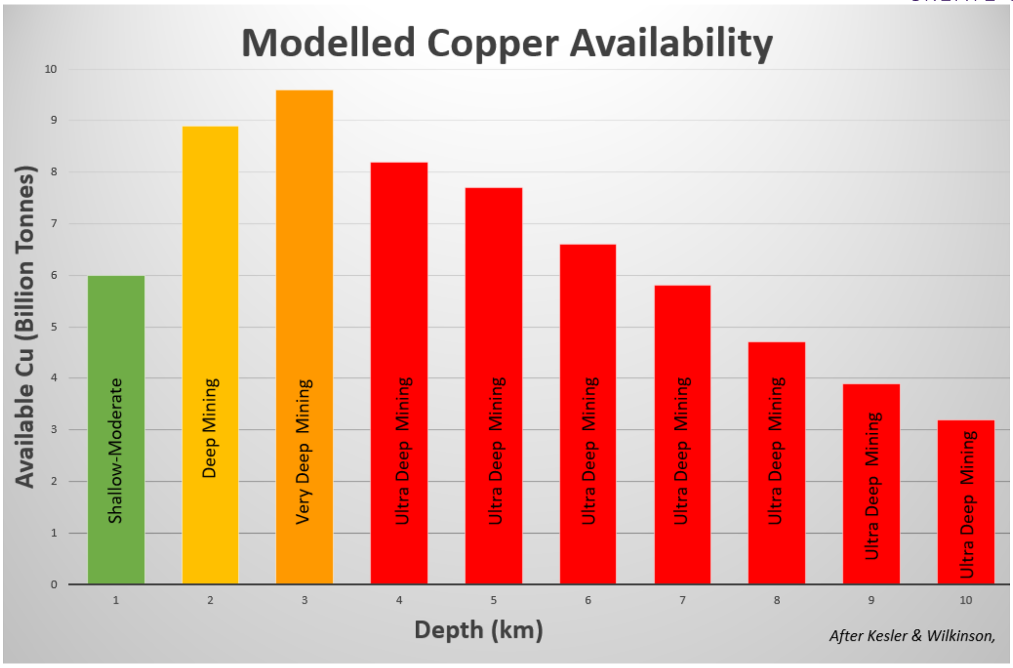

Figure 1. Future copper availability as a function of depth (after Kesler et al, 2008).

1.1.2 Copper Demand

Although growth in copper production appears exponential, Singer (2017) demonstrated a linear relationship between population growth and copper demand (as depicted in *Figure 2*a). Moreover, Singer predicts that the demand for copper will increase in the short term as populous nations such as China and India develop increasing per capita incomes, with demand levelling off as their economies improve and become less reliant on copper. Most current projections (e.g., Elshkaki et al, 2016) place copper demand at around 50 Mtpa by 2050 (as depicted in *Figure 2*b)., partly driven by the worldwide energy transition to renewables.

The argument that higher copper demands will drive up the price of copper, and that this in turn will unleash many low-grade deposits that are currently uneconomic, is optimistic in that it does not account for the fact that many of the shallow deposits are difficult to access and exploit due to ESG pressures, whilst many of the underground deposits are deep and extremely difficult to mine using conventional mass mining methods.

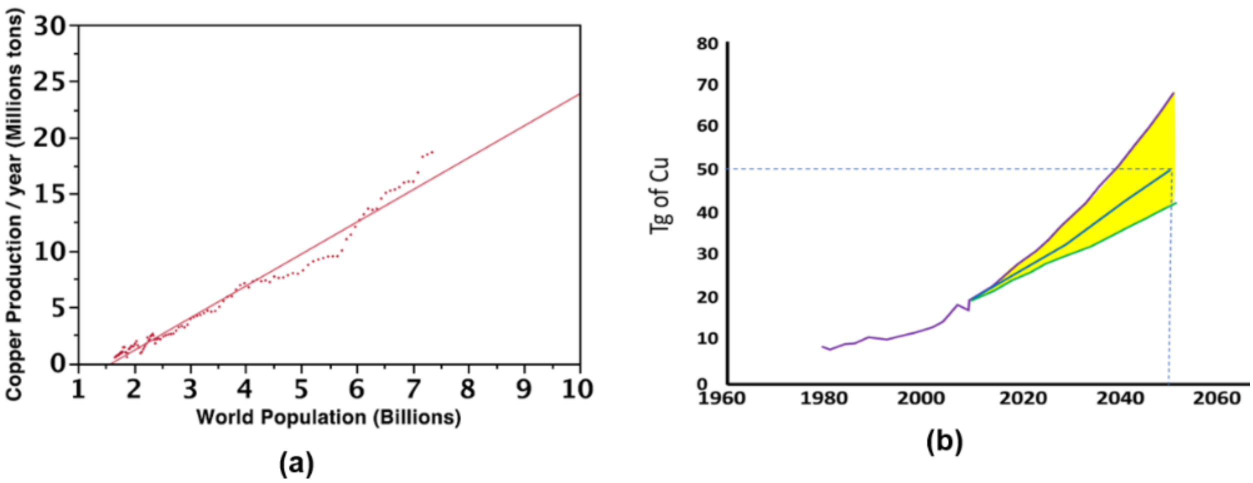

Figure 2.(a) Copper production versus world population, after Singer et al, 2017. (b) Global copper demand for the four GEO-4 scenarios (~50 Mtpa by 2050), after Elshkaki et al, 2016.

1.2 Underground Mass Mining

Underground mass mining methods are the only means of economically mining deep, massive, lower-grade deposits. The most common mass mining methods employed are large blasthole open-stoping, sublevel caving, and block (or panel) caving; the latter offering the lowest mining costs/tonne and is most comparable to conventional open pit mining.

1.2.1 Surface Mining Limitations

Open pit mining is clearly the most economic mining method for extracting large tonnages of ore near surface, however, increasing open pit depths are accompanied by increasing mining / geotechnical risk and escalating costs. Typical constraints facing deep open pits include:

- High strip ratios, resulting in the mining of excess waste rock.
- Large mine footprint, comprising the large pit area and associated waste rock dumps.
- Equipment congestion, as the pit base narrows, and more haulage trucks are required to maintain production levels.
- Mounting ESG pressures, typically associated with the large mine footprint impacts.

It is common industry practice, where an orebody extends to surface (or near surface), that open pit mining is initially undertaken to provide an early return on the investment and initial capital funding for the underground mine. In many cases, the depth and life of the pit is dictated by the length of time required to develop the underground mine and bring it into production.

1.2.2 Cave Mining

Block cave mining has been regarded as a relatively new mining method in Australia, with Northparkes Mines commissioning the first Australian block cave in 1996. However, the method is well over 100 years old and has been successfully implemented worldwide. Early cave mines (generally those developed pre-1990s), were typically characterised by weak rock masses and block heights that were not larger than the width of the footprint. The present resurgence in cave mining methods has been spawned by the fact that the future mining of most base metal deposits increasingly lies underground. However, many of these deposits are lower grade (average grade < 0.5% Cu, e.g.) and their economic viability relies on our ability to extract very large tonnages of ore at low cost (e.g. PT Freeport Indonesia caves which collectively yield upwards of 100,000 tonnes per day at a mining cost of less than USD 10/tonne).

Despite the low operational cost of the method once commenced, cave mining is capital intensive, with most large cave mines costing between USD 1-10 billion to construct, over a 3-15-year period, and expended completely before a single ounce of ore is hoisted. For this reason, modern miners no longer cap the height of blocks to be caved to less than 250m; but instead seek to maximise the height of the cave block, so as to reduce capital spend and mining costs (as illustrated in Figure 3). The popular trend to deep, high-column cave mines translates to a much higher level of risk: in the form of cave performance, underground infrastructure stability, and resource recovery; all of which calls for the fundamental research to identify and mitigate the potential issues.

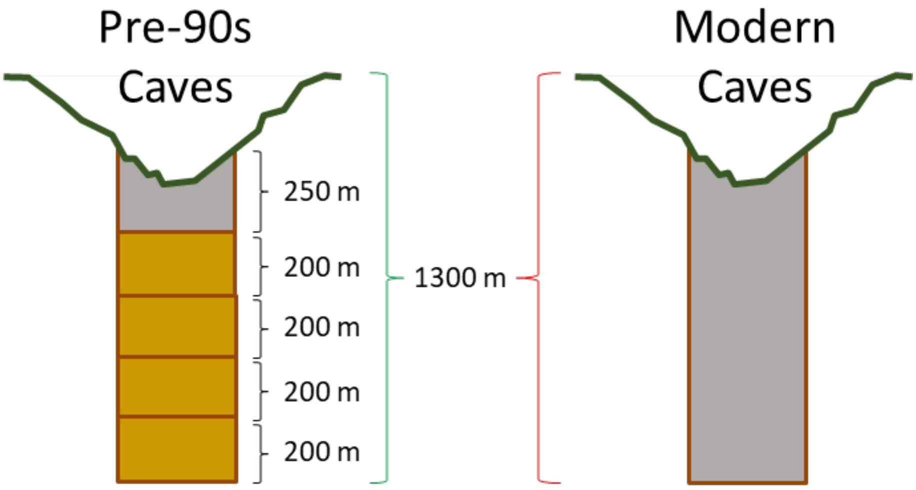

Figure 3. A schematic illustrating the modern trend of increasing cave block height (based on actual cave mine examples).

2. Challenges With Deep Cave Mines

According to Jakubec (2018), there are currently over 50 cave mining projects being investigated around the world (refer to Figure 4), most of which have their production level located deeper than 1km below surface.

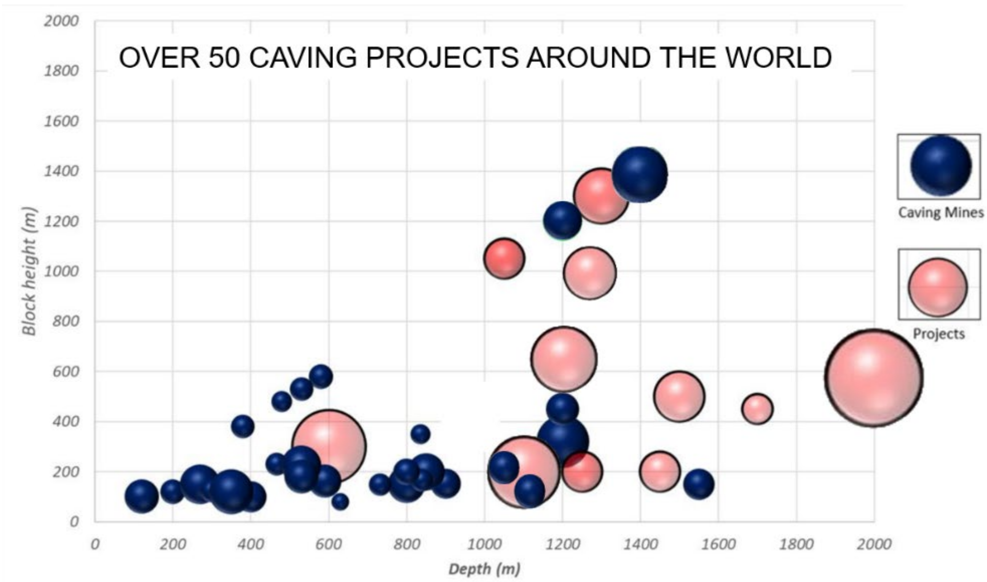

Figure 4. Current cave mining projects and their planned depth below surface; note that the size of the sphere represents the relative size of the deposit.

To date the success of deep, high-column, cave mines has been mixed. Many argue that most cave mines have proved highly successful, where success is defined by the mine's profitability and ability to yield positive shareholder returns on investment. However, technical success is far more elusive, with most modern cave mines experiencing some form of underperformance; notably attributed to unforeseen geotechnical issues and culminating in loss of resource and/or higher operating costs than were predicted by the feasibility study, relied upon by the mining company board to justify the mine development.

2.1 Context

In the new generation of "super caves", block and panel caving are being applied to: generally, but not necessarily, stronger orebodies; to deeper and sometimes "blind" orebodies subject to higher stresses; to lower grade orebodies; and to greater caving block heights than has previously been the case. Production rates of well in excess of 100,000 tonnes of ore per day are being planned in several cases, (Brown, 2012).

The tension between rock mass strength and in situ stress is the 'age-old' driver of mine stability (mineability) and dictates the success of the mining method. To this end, it is imperative that the rock mass is well characterised in terms of strength; both for the orebody and the surrounding host rocks, in order to model and predict performance of the mine. McCarthy (2002) suggested that the geo-risks to be addressed in deep mining feasibility studies must include:

- increased geological risk due to sparse data density,
- increased capital risk due to the higher cost of establishing the mining operation, and
- increased technical risk due to the challenging environment for materials handling, ventilation, services, employees, and ground control.

All of the above risks can be grouped into geotechnically-related risks, particularly for cave mines, and this is elaborated on further below.

2.2 Extensive Volume to be Characterised

It is important to understand that rock mass characterisation of any mass mining method not only includes the deposit, but also the host rocks; as these generally contain critical infrastructure such as shafts, access drives, conveyor drives, crusher chambers, surface tailings facilities, and the like. Furthermore, it is not uncommon for the host rocks to overlay the deposit and, consequently, comprise the main source of dilution. Thus, even a relatively small deposit (for example, a deposit that is 300 m x 300 m and at 1000 m depth below surface to the production level) the volume of the block of ground to be characterised in detail may prove to be in excess of 1.6 x 10^9 m^3, and to cover a surface area in excess of $10km^2$.

The amount of geotechnical data required to develop a representative geotechnical model of such a vast volume is significant; particularly where the rocks are of variable strength, as is common for most porphyry copper deposits. Therefore it is imperative that detailed geotechnical data is acquired starting right from the exploration phase. The deeper the orebody, the more difficult and costly it is to drill, and the longer it takes to acquire data. Its is the author's opinion that the greatest risks to any cave mine are geotechnical in nature. If the quality and quantity of detailed geotechnical data are not substantially improved, then any unpredictable rock mass response, resulting in poor performance of future cave mines, may lead to nervousness about the use of cave mining methods as viable mining options due to a lack of investor confidence.

2.3 Extreme Conditions

It stands to reason that the deeper the mine, the greater the magnitude of the stresses that drive rock mass failure. This is further complicated by the fact that stress measurements are often unreliable, particularly in fractured rock; such as that commonly found in copper porphyry deposits.

Stress-induced rock-mass deformations (such as the squeezing depicted in Figure 5) can generally be managed through the application of rock reinforcement and ground support systems; however, the intensity of these systems is a key component of the development advance rates that the mine is able to sustain. Given the significant amount of development required to put a cave mine into production (e.g., the Grasberg cave comprises 350,000 m of development), even slight underprediction in development rates (attributed to ground conditions) can culminate in significant development cost overruns and, most importantly, lead to significant delays in the commencement of mine production.

Figure 5. Example of squeezing ground conditions experienced at Cassier Mine in Canada, ultimately contributing to its premature closure.

2.4 Caveability & Cave Propagation

Caveability in a caving mine is the measure of the ability of an orebody to cave after it has been undercut over a given area. Kendorski (1978) in his paper "The caveability of ore deposits", states that any rock mass will cave if a large enough area is undercut (typically defined as the critical hydraulic radius - HR_{cr}). However the extent of the area required to initiate and sustain continuous cave propagation is clearly a function of rock mass strength and stress.

Modern, deep, high-column, cave mines have demonstrated that the HR_{cr} required to initiate caving differs from the area required to sustain continuous cave propagation (i.e. the HR_{cr} necessary for the entire column); and cave back stalling (cave back 'hang-up') or cave back 'overhangs' may form, resulting in potential:

- reduction in production rate whilst caving is induced through expensive and time-consuming cave inducement techniques,
- partial loss/sterilization of ore,
- significant loss/sterilization of the remainder of the cave block.

The Northparkes, E26 Lift 2 (NPM L2) block cave (refer to Figure 6) provides an excellent case example of how an irregular cave back (depicted by the red shape in Figure 6) can form during its propagation. In the NPM L2 case, the undercut was initiated in a weaker rock mass which failed more readily than the adjacent, more competent rock mass. As a result, the cave propagated more rapidly in the weaker rock and effectively destressed the more competent rock, thereby preventing it from undergoing the stress-induced failures required for its propagation. The ultimate consequence of such an uncontrolled, irregularly shaped cave propagating rapidly upwards, is to dilute or even sterilize the uncaved ore.

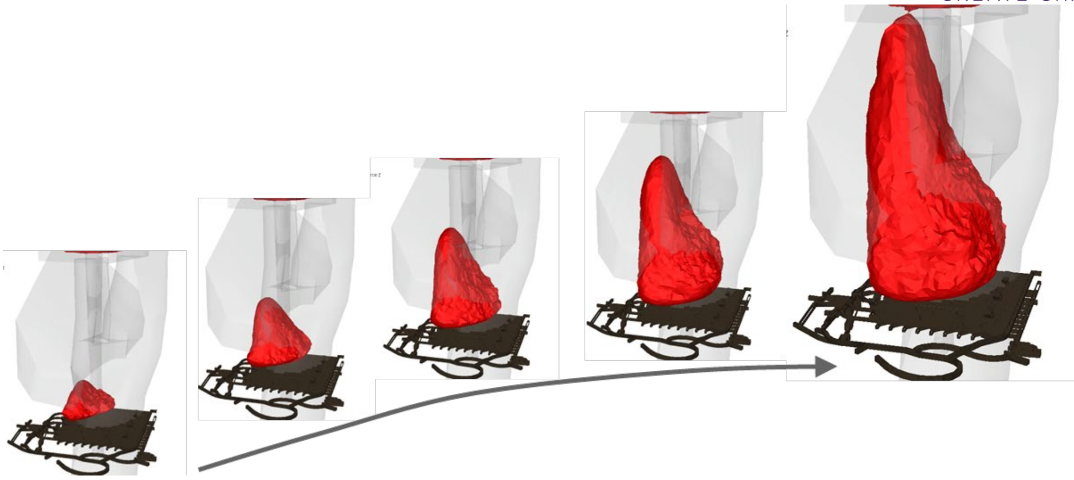

Figure 6. The Northparkes, E26, Lift 2 block cave propagation over time.

It is clear that a cave mine's productivity and economics are often dictated by the rock mass' caveability, and hence the ability of mine-designers to:

i. accurately predict the size of the undercut area required to initiate and sustain cave propagation (HR_{cr}), as well as

ii. predict the evolving shape of the propagating cave back,

both of which are critical to successful recovery of the orebody through cave mining.

2.5 Resource Recovery Constraints

The issue of incomplete/partial caving, as discussed in the preceding section, is particularly important for deep, high-column caves, as the percentage of ore 'locked up' in periphery of the cave tends to be significant (compared to low-column caves), as illustrated in the Northparkes Mines case in Figure 7. It is common practice for the quantity of unrecoverable ore occurring around cave peripheries to never be factored into the resource recovery estimates during mine feasibility studies.

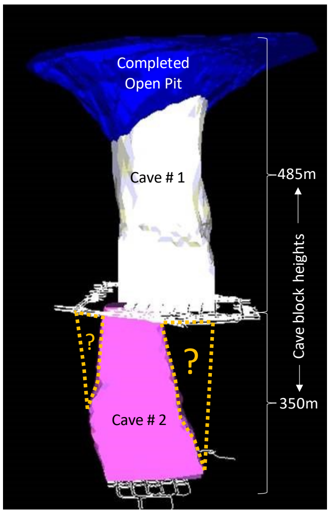

Figure 7. Isometric view of the Northparkes Mines, E26 Lift 1 (white) and Lift 2 (pink) block caves. The volumes defined by the orange dotted line indicate lost ore due to the incomplete caving around the Lift 2 cave periphery.

Another major issue that is rarely accounted for in cave resource recovery estimates is that of isolated draw and early dilution entry. Isolated draw refers to the mechanism of rapid isolated material flow within caves where drawpoint spacings are spaced too widely apart to cause mass flow of the overlying caved material. The consequence of isolated draw is to facilitate the rapid migration of overlying dilution into the drawpoints (as depicted in Figure 8), thereby diluting the grade of the extracted material; at worst it may even serve to sterilise ore.

Modern, deep, high-column cave mines typically design for widely spaced drawpoints to ensure their stability against higher vertical stresses; however, this leads to isolated draw with early dilution entry. Higher levels of dilution are inevitable and commonplace in modern cave mines, yet are rarely accounted for in predictive recovery models.

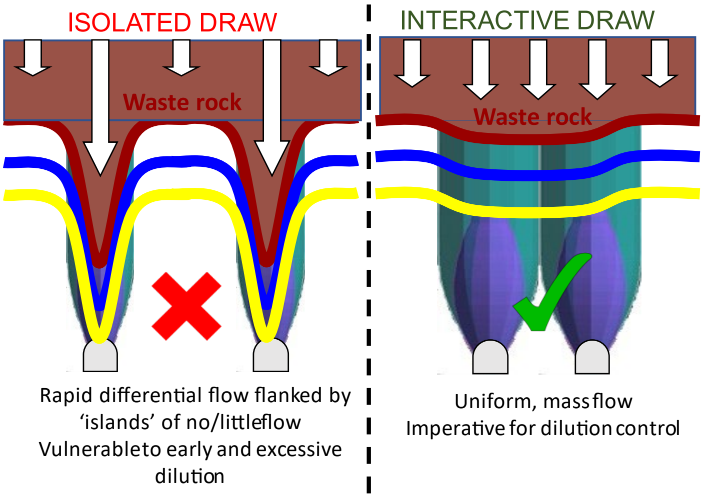

Figure 8. Illustrating the concepts of isolated draw vs interactive draw and their effect on material flow in a cave.

Another significant consequence of isolated draw is the fact that it results in the concentration of vertical stresses (i.e., due to the weight of the overlying column of ore) into the areas of stagnant/slow flow occurring between the isolated draw zones (as depicted by the left diagram in Figure 8). This concentration of vertical stresses is transmitted down onto the drives and drawpoints on the extraction level below, thereby effectively point-loading the rock mass (pillars) around the excavations and which may cause them to fail (as depicted in Figure 9).

Figure 9. Example of where the vertical stress concentrations point loaded a drawpoint area causing the apex pillars to fail and the drawpoint becoming inaccessible.

2.6 Cave Subsidence on Surface

Cave mining subsidence is not, in itself, a deep cave mine related problem, although it can be argued that a deep cave mine should result in a greater surface manifestation than a shallower cave of the same footprint dimension if the depth of the crater increases (i.e. greater tonnages are drawn because columns are higher).

Following the propagation of the cave through to surface, in response to progressive extraction of the orebody, the cave subsidence zone will continue to expand and deepen as long as the orebody continues to be drawn. Unlike near surface tabular mines (e.g. coal mines) which are characterised by the extraction of a relatively narrow horizon (e.g. a coal seam) and which result in the non-destructive lowering of the earth's surface, or 'continuous subsidence, cave mines are characterised by destructive, 'discontinuous subsidence' of the surface; this is typified by significant vertical deepening of the surface (crater) bounded by a zone of extensive tensile cracking and surfaces failures, as illustrated in Figure 10.

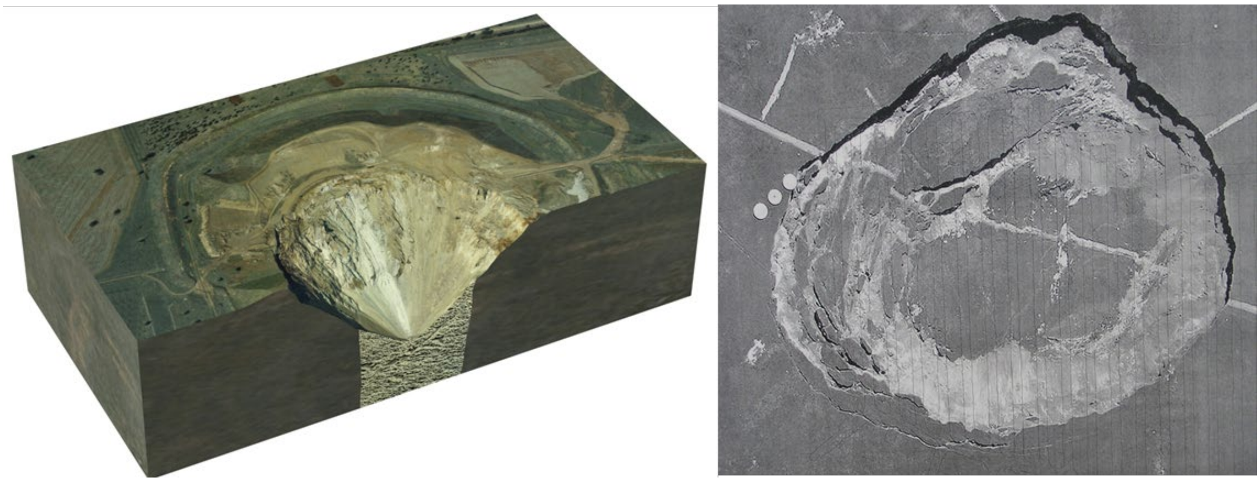

Figure 10. Examples of cave mine surface subsidence zones (left Northparkes Mine, right Ridgeway Mine).

It is important to note that cave induced surface subsidence deformation zones are dynamic, hence the nature and extent of deformations (and zones) changes over time as a result of changes in mining activity (production draw) and mining depth. As mining depth increases, the extent of subsidence deformations also increases and, in many cases, the nature of the deformations (failure modes) changes. This dynamic evolution of subsidence deformation with increasing mining depth makes prediction particularly difficult, yet increasingly more important, for mine-planning.

Not only is it imperative that the mining engineers locate all critical infrastructure outside of the influence of the cave subsidence zone, but the engineer needs to understand and predict the effects on subsurface groundwater flows and associated environmental impacts. Environmental impacts caused by cave subsidence can be the very difficult to manage and comprise major issues of community concern. Valenta, et al, (2021) have correctly identified ESG issues as being the major showstoppers of most new mining operations; this is especially the case for cave mines where surface subsidence has proved to be the most contentious social and political hurdle currently facing mining companies today. In terms of mining impact, it is relevant to point out that caving operations have a smaller footprint compared with open pit operations.

2.7 Deep Cave Mines = Low grade Deposits & High Capital Investment = High Risk

The challenges attributed to deep cave mines, described above, have for the most part been largely ignored by the mining industry. Cave underperformance is typically ascribed to geotechnical factors that were either not identified during mine feasibility studies, or their impact poorly predicted by the models used to establish the mine design criteria. In some cases, this may be true, however the ultimate consequence is to erode investor confidence in cave mining methods, because geo-risks to cave performance are underappreciated.

It is the author's opinion that shareholders are often ill informed about the technical risks in cave mines, because miners fail to adequately incorporate these risks into project evaluation. This is partly because they themselves are simply applying mine designs that have worked in the past, to deeper, more complex deposits located in mining environments that are far less forgiving - and expecting a similar outcome. Furthermore, the scale of new large underground mines ('Super Caves') can be over five- to 10times that of cave mines in the past and, hence, the capital at risk is substantially higher. A classic example, of such a large scale cave mine, is PTFI's Grasberg mine which comprises over 2,400 drawpoints spread over a footprint area of 720,000 m^2, resulting in over 350,000 m of linear development including accesses, ventilation drifts, ore flow systems, fixed facilities and production areas (refer to Figure 11). Much of this development and construction must be in place before any production can commence, hence several billions of dollars are invested prior to any return of capital or an appreciation of cave performance.

It is, therefore, imperative that mining studies incorporate risk into their technical, recovery and financial models so that investors can appreciate whether the stated NPV represents a central estimate for the mine investment.

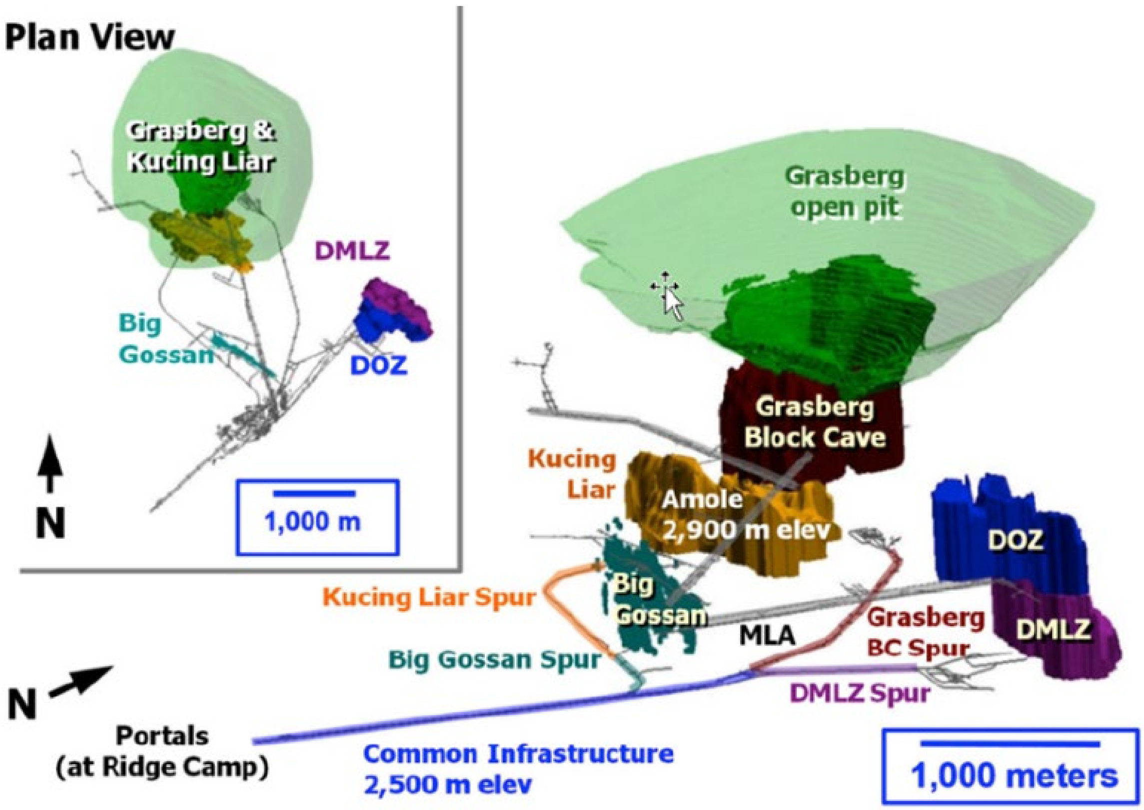

Figure 11. Mine-wide isometric showing the extensive infrastructure and various cave mines in the PTFI operation.

3. DMG Research Addressing Deep Mass Mining

The WH Bryan Mining Geology Research Centre (BRC), within the Sustainable Minerals Institute at the University of Queensland, has formed a 'Deep Mining Geosciences' (DMG) group which is tasked with developing a strong industry-collaborative programme of applied mining research and education, in the area of Deep Mining Geoscience. The DMG group aims to bring world-class geoscientific insights into all stages of discovery to recovery of ore deposits, including mine planning, development, and effective operations.

In an effort to address the challenges of mass mining at depth, the DMG group met with technical personnel from several of the major mining companies with the objective of identifying key issues to tackle through well formulated and focussed research and training. To this end, DMG research will focus on six key areas that encompass the majority of the issues identified by the mining industry, and where coordinated collaboration and resources will facilitate the much-needed step-change required for deep mass mining design and operations.

The 6 key areas include:

1. Geoscience Characterisation,
2. Rock Mass Conditioning,
3. Deep Mass Mining Geo-Risk Management,
4. Material Flow in Deep Cave Mines,
5. Mining Method Design Improvements, and
6. Education.

3.1 Geoscience Characterisation

As described in section 2.2, the task of adequately characterising a massive ore deposit (and its host rock) so as to develop reliable geo-models on which mine design can be based, and mine performance predicted, is a vast undertaking that has yet to be achieved within the mining industry. Not only is there a lack of understanding and consensus within the industry over governance requirements for geoscience inputs into resource and reserve models, but there is also still considerable debate and uncertainty over fundamental questions, such as:

- What data should be collected for each phase of study (from exploration through to mine closure)?
- How much data are enough for each phase of study (from exploration through to mine closure) and how can we quantify data sufficiency for model construction?
- How are data from various sources integrated (i.e., integration of geological, geophysical, geohydrological and geotechnical data sets) and used to construct geo-models?
- How can we better characterise the ore deposit between drill holes (both ore and waste rock), recognising and quantifying data uncertainty and translating this information into model reliability?
- How can we characterise an ore deposit faster and more accurately and effectively?
- Are there new enabling technologies and/or methods that can improve the characterisation process?

DMG research will focus on rock mass characterisation for deep mass mining methods, with the goal of addressing the following objectives:

1. Improve the quantity & quality of geo-data through the integration and rapid processing of multiple geo-data sources. This data-fusion will serve to improve data utilisation (extract more information) and also seek to extract data from new/enabling technologies.
2. Improve the speed at which data are processed through automation tools (software).

3. Develop/improve on present geostatistical methods and tools that serve to quantify data sufficiency, as well as data adequacy, for geotechnical modelling. It is envisaged that these improved methods will bring greater clarity and guidance on the definition of 'modifying factors' for deep mass mining within the JORC Code[1].

4. Develop/improve geostatistical methods

3.2 Rock Mass Conditioning

The introduction of rock mass preconditioning for cave mines was demonstrated by van As and Jeffrey (2000) as early as 1997, as an effective means of improving the caveability of cave mines with competent rock masses. Subsequent mine site research in the early 2000s demonstrated that the emplacement of hydraulic fractures into the rock mass serves to significantly alter the rock mass strength and local stress regime, all of which assists in the engineering of the rock mass response to mining. Following this ground-breaking work at Northparkes Mines, several mining companies have since adopted the technology as part of their cave mining process; the benefits have largely been realised in improvements in rock mass caveability and a reduction in the violent rock mass response to high stresses (i.e., rockbursts).

Unfortunately, over the past two decades little new research has been undertaken on rock mass preconditioning; instead mining companies have relied on anecdotal evidence to justify the application of hydraulic-fracture preconditioning without fully understanding 'how' and 'why' it is successful. Consequently, these rock mass preconditioning programmes lack a technical basis for design and, hence, many prove suboptimal and ineffective.

In addition to better understanding the impact of preconditioning techniques on modifying the rock mass characteristics, research into quantifying seismic (rockburst) damage to the rock mass is also needed to gain an appreciation of the resulting degradation of rock mass strength. The development of tools and methods for quantifying seismic induced rock mass damage will prove particularly useful in the design of remedial ground support systems.

For any applied mining research, the best experimental data are derived from a mine-scale trial, or by actual mine-scale application during operations. DMG research proposes to concentrate on analysing hydraulic fracturing data, rock mass damage data and monitoring data from several cave mines over the past two decades. The objective of this is to:

1. Understand the conditions and mechanisms through which hydraulic fracture emplacement effectively alters the rock mass and local stress regime. Develop methods for quantifying the effects of preconditioning on the rock mass.

2. Identify the geo-impact of various rock mass preconditioning technologies and evaluate their effectiveness in addressing key mining risks at depth.

3. Based on the above, develop effective rock mass conditioning strategies for mitigating against deep mining risks.

4. Qualify the influence of temperature and stress on the effectiveness of rock mass preconditioning methods to manage deep mass mining hazards.

5. Quantify rock mass strength reduction induced by large seismic events, through the application of novel tools and processes.

3.3 Deep Mass Mining Geo-Risk Management

The ability to identify and quantify risk and uncertainties in mining method selection, mine design, mine planning and construction, and mine operations depends on how well the geology and geotechnical characteristics of a deposit are understood. Data uncertainty increases decision uncertainty and amplifies risk

[1] The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (the JORC Code) establishes standards for public reporting, emphasising principles of transparency and materiality.

irrespective of the type of mining; but it has a greater impact in caving, owing to the method's inflexibility and, thus, inability to recover from adverse mining events. The issue of data uncertainty and variability will be covered by research conducted under the geoscience characterisation research discussed above (point 4 of section 3.1).

It is imperative that geohazards are identified and incorporated into mine design in a useable way, and consequently managed effectively during operations to minimise their impact on mine-performance.

DMG research will focus on the identification, quantification, and effective management of geohazards through:

1. Back analysis of existing mine monitoring data (i.e., stability monitoring, stope/cave performance monitoring, and recovery [grade] data) to develop/improve tools and methodologies for defining and assessing key geohazards (thereby developing key hazard indicators), and then incorporating these into a mine geohazard model.
2. Developing guidelines on methods for incorporating potential geohazards into predictive mine performance models (including ore recovery models) during mine study phases. It is envisaged that these methods will bring greater clarity and guidance on the impact of geotechnical, geohydrology, and geometallurgical 'modifying factors' for deep mass mining compliance to JORC.
3. Developing/improving methodologies/tools for integrating the mine geohazard model with geotechnical monitoring systems and real-time operational (e.g., undercutting and production) databases for effective real-time geohazard management during the operational and closure phases of mining.

3.4 Material Flow in Deep Cave Mines

As discussed in section 2.5, the design layout for deep cave mines attempts to satisfy two competing design criteria when specifying the drawpoint spacing, the first of these is the stability of the drawpoint pillars, and the second is the effects of interactive draw between drawpoints. The wider the drawpoint spacing, the greater the drawpoint apex pillar dimensions and, thus, the greater the stability of these apex pillars when subjected to the high vertical loads of the cave column above. Conversely, the wider the drawpoint spacing, the less material flow interaction occurs between drawpoints and, thus, the greater the dilution potential and less control on cave performance, through systematic drawcontrol strategies.

DMG research will undertake fundamental, lab-scale studies; as well as back-analyse mine flow data, cave propagation monitoring data, and production draw data to:

1. Investigate the mechanisms of drawzone growth, drawzone interaction, and mass flow under high vertical loads (high cave columns), through:
   - back-analysis of industry cave tracker, smart marker technology data, and draw data.
   - supercomputer (parallel processing) DEM modelling.
   - bespoke physical modelling for deep, high column, mass flow.
2. Investigate mechanisms of dilution entry and dilution control.
3. Quantify the primary causes of ore reserve losses in modern caves:
   - Develop guidelines for the Inclusion of dilution predictions into resource recovery models.
4. Investigate effective load-shedding (stress), draw strategies.
5. Development of integrated, real-time drawpoint monitoring tools to manage (automate) draw control:
   - Monitoring/scanning tools for tracking drawpoint and muckpile changes and integrating this information with production (i.e., reserve reconciliation tools),
   - Real-time deformation and stress monitoring data integration, with draw control to provide draw strategies for the effective management of drawpoint instability.

3.5 Mining Method Design Improvements

The application of conventional mass mining methods to exploit deep, massive, low-grade deposits has proven to be challenging, with the risk of successful recovery increasing with increasing mining depth, as discussed in section 2. Alternative, new or modified mining methods are becoming increasingly necessary to avert the uncertainty risks associated with current deep mass mining methods. At the very least, the mining industry requires a system to quantify the risks in terms of personnel exposure, ore loss, capital overruns, and operating cost overruns.

DMG proposed research will focus on:

1. Investigating robust mass mining methods to better suit deep underground mass mining. This will include:
    - a comparison of existing mining methods,
    - the development of new and/or modified mass mining methods (e.g., variants of Inclined Caving) that are better suited to withstand high stress conditions.
    - an evaluation of effective undercutting strategies and methods for deep cave mines.
2. Developing a selection of robust performance tests/criteria, to evaluate and quantify the pros and cons (uncertainty risks) of new and existing mining methods; ultimately demonstrating their reliability/suitability to deep mining environments.
3. Investigating methods of reducing surface subsidence effects, including the emplacement of in-pit tailings or waste rock above an active cave mine (note that this research will also address the associated inrush risks).
4. Investigate the combination of hydraulic fracture, rock mass preconditioning with in-situ leaching technologies, to improve ore recoveries from cave mines. The emphasis will be on mines that are comprised of weak rock masses and are prone to large extraction level collapse, and those characterised by regions of uncaved ore (i.e., overhangs/underbreaks, etc.).

3.6 Education

Over the past two decades, the mining industry has suffered from a worldwide decline in the number of mining-related students and, consequently, there is a desperate shortage of skilled mining personnel in the mining industry. This has been further complicated by increasing mining school closures and a decline in experienced lecturers and researchers.

To meet the growing demand for mining professionals, the University of Queensland (UQ), through its various schools, provides various degrees majoring in mining engineering, geotechnical engineering, geology, and a variety of geosciences. In addition, UQ's 'Sustainable Minerals Institute' (SMI), has developed a number of complementary professional development programmes for the resources sector, to increase mining specialist knowledge and skills. To this end, the BRC, through its Deep Mining Geoscience (DMG) group, is developing a 'Mass Mining' professional development programme to complement its existing range of professional development courses, as listed on the SMI website https://smi.uq.edu.au/PD-Geology-Mining-Metallurgy.

The objective of DMG in education is to:

1. Ultimately provide UQ with a world-class Masters programme in 'Underground Mass Mining' that is characterised by a distinct practical focus, using real case studies and hands-on, practical exercises that demonstrate the theoretical basis for mass mining that is relevant to current mining practice.
2. Provide the industry with a world-class- professional development programme in Cave Mining' that comprises of several modules spanning the various phases of mining from conceptual studies through to cave production. Each modules covers various topics specific to cave mining, ncluding rock mass characterisation, cave mine design, caveability, cave fragmentation, cave subsidence, cave

management, major hazard management, etc. A more detailed listing can be found in the appendix and online at https://smi.uq.edu.au/deep-mining-geoscience.

3. Provide industry relevant research (as described in the preceding sections) with clear objectives and which is delivered through the provision of industry funded students/researchers.

This will be achieved through:

- Formalised, long-term partnerships between SMI and key mining companies that are designed to meet the mining industry's educational/professional development objectives, in both the short and long term.
- Unconstrained industry collaboration with guaranteed access to key data (without this the mining industry's investment in this area will not return its potential).
- Collaboration with key universities, research institutes, and industry experts that will enable the continued growth of specialist expertise across a wider group (i.e., succession planning for Subject Matter Experts (SMEs)).
- A pipeline of sustained resources (funding, students, mentors, company champions).
- Unconstrained publication of key research (this is essential and needs to be an understood part of all research projects).

To ensure success, it is imperative that our industry partners actively participate in all research projects. Ideally, each research project should effectively be manned by an accomplished research candidate/s seconded from at least one of our industry partners. Furthermore, the appointment of an industry 'project champion' has proven to be an effective means of facilitating active industry collaboration and communications between all stakeholders.

3.7 Vision for DMG

The objective of DMG research is to provide the mining industry with step-change solutions to deep underground mining issues. These issues are complex and as such they demand the collaborative efforts of experienced practitioners and SMEs supported by the collective resources of industry partners, in the form of data, funding and dedicated technical personnel.

Thus, DMG will seek to form a strong research group comprising of a combination of industry and university experts, all supported by a team of world-class postgraduates and post-doctoral researchers. This group will then operate in sub-groups, each focussing on one of the five research areas.

To achieve this ambitious goal, DMG will seek industry commitments to guarantee support over 6-year blocks (i.e. to support two PhD terms). Where each of the five sub-groups (research areas) will focus on select topics (as outlined above and to be confirmed by industry), be governed via a well-defined programme of work and managed by a steering committee comprising of select UQ academics, consultant SMEs and industry champions.

4. Conclusions

Within the SMI, the WH Bryan Mining Geology Research Centre, recognises that the future of mining involves underground methods, and that only deep mass mining of ore deposits will be able to provide the quantities of minerals necessary to meet society's and the world's increasing demand for these resources. Until recently, mass mining methods have only been utilised to extract shallow to intermediate-depth orebodies; but, the past two decades have witnessed a resurgence in underground mass mining methods that are planned for much deeper (>1000 m production level) deposits; and these mining developments have come with new challenges and substantial risks.

To this end, the BRC formed the DMG group, which has been tasked with undertaking research into deep mass mining, that is focussed on five research areas that representatives of the mining industry identify as key; and these five incorporate the majority of the technical issues identified so far by the mining industry.

1. Geoscience Characterisation,
2. Rock mass Conditioning,
3. Deep Mass Mining Geo-Risk Management,
4. Material Flow in Deep Cave Mines, and
5. Mining Method Design Improvements.

In addition to research, DMG will also develop postgraduate education training in the form of a 'mass mining' professional development programme which will serve to address a major skills shortage in underground mass mining.

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6. Appendix – Potential Projects

A brief outline of DMG research projects is outlined below. It is important to note that the scopes of these projects are fairly broad and will be tailored to suit industry sponsor's needs.

3.8 Geoscience Characterisation

The following proposed projects seek to meet the objectives described in section 3.1.

1. **Geoscience Data Fusion:**

   The projects will focus on integrating data from core logging, geophysical logging (down-hole logging and sub-surface scanning), tomographical data, scanning data (including hyperspectral scanning), measure while drilling (MWD) logs and various laboratory (strength) tests. The goal being to objectively output sufficiently large quantities of high-quality properties and parameters necessary for characterising the rock masses comprising the deposit.

   Many of the scanning, type logging technologies are novel and require a detailed analysis of their output to investigate their potential for quantifying key geoscience parameters.

   The project will also investigate the automation of data processing along with machine learning (ML) algorithms for the automation of data interpretation. The ultimate objective being to remove manual subjectivity, and accelerate the process of data acquisition, data processing and data interpretation for the rapid generation of 3-dimensional models of key rock mass characterisation parameters and classification indices.

2. **Representative Rock Mass Model Generation:**

   The project aims to apply novel geostatistical methods to develop reliable and representative rock mass models that truly honour the quantity and quality of the data. In addition to model generation, novel geostatistical methods/tools will also be developed to quantify the data sufficiency and data adequacy of the data used in the model construction. The intention is to replace existing subjective criteria used to define model maturity with quantifiable indices (e.g., level of confidence in key geotechnical parameters), currently captured under 'modifying factors' within the JORC Code.

3.9 Rock Mass Conditioning

The following proposed projects seek to meet the objectives described in section 3.2.

1. **Hydraulic Fracture Rock Mass Conditioning:**

   The project will focus on back-analysing existing hydraulic fracture (HF) and blasting preconditioning data, geotechnical monitoring data, mine-through mapping data, cave fragmentation data and cave performance data to investigate the primary mechanisms through which hydraulic fracture emplacement and blasting effectively alters the rock mass and local stress regime.

   Through the identification and understanding of the dominant HF and blasting mechanisms that occur in fractured hard-rock mass, common to the mass mining industry, the objective is to develop effective rock mass conditioning strategies for mitigating against deep mining risks and engineering cave performance.

2. **Alternative Hydraulic Fracturing Applications for Cave Engineering:**

This project will focus on investigating new applications of HF technologies to engineer (enhance) cave performance and improve recoveries. Further details into this project will be made available to industry following the endorsement of confidentiality agreements between stakeholders.

3.10 Deep (Mass) Mining Geo-Risk Management

The following proposed projects seek to meet the objectives described in section 3.3.

1. **Cave Geohazards Prediction:**

   This project will examine mining and geotechnical data to identify/verify key indicators (precursors), that contribute to the triggering of significant geotechnical events. The application of novel geostatistical and machine learning (ML) algorithms will be employed to back-analyse data from several (participating) mines to identify and quantify key hazard indicators. The objective being to develop more reliable tools for the prediction and management of geohazards in real-time, including the recommendation of effective mining strategies.

2. **Cave Performance Risk Evaluation:**

   The focus of this work will be to examine the past cave performance of several (participating) cave mines in terms of ore loss, the deviation of drawpoint dilution ingress and grades (compared with predictive models), and ore recovery. The objective being to identify the common geo-risks associated with poorer (than predicted) cave performance and quantify their impact so that they can be incorporated into predictive models (including resource recovery models).

3.11 Material Flow in Deep Cave Mines

The following proposed projects seek to meet the objectives described in section 3.4.

1. **Rock Flow in High Column Caves:**

   The research will revisit the fundamentals of material flow in caves under high column loads using both physical and numerical modelling methods supported by the back-analysis of various mine data (cave trackers, smart markers, geo-markers, cave monitoring, production data, undercut data, etc.). The objective is to test whether interactive draw and mass flow can be achieved in high column cave mines and quantify dilution entry as a function of drawpoint spacing over the life of the cave.

2. **Stress Management in in High Column Caves:**

   As with the above research, using existing mine data, this project will examine / back-analyse the causes of stress concentrations and instability on the extraction level under high column loads with the aid of both physical and numerical models. The objective is to quantify the effectiveness of increasing drawpoint spacing to ameliorate against point loading resulting from high cave columns and to assess the effectiveness of 'load-shedding' draw strategies. Novel methods for promoting mass flow, reducing dilution and ameliorating against high column stresses will also be investigated.

3. **Real-time Draw Control:**

   The project will use data fusion tools to integrate geotechnical monitoring, cave monitoring and cave production data to develop ML algorithms that manage (automate) effective draw control strategies to prevent early dilution entry, reduce dilution ingress and reduce extraction level damage due to cave column loading.

3.12 Mining Method (Design) Improvements

The following proposed projects seek to meet the objectives described in section 3.5.

1. **Novel Mining Methods for Deep Underground Mass Mines:**

   The research will use a suit of numerical modelling tools to examine the effectiveness of existing and new mining methods in minimising the geo-risks associated with deep underground, mass mining. In addition, the project will seek to develop a selection of robust performance tests/criteria, to evaluate and quantify the pros and cons (uncertainty risks) of new and existing mining methods; ultimately demonstrating their reliability/suitability to deep mining environments.

2. **Cave Subsidence Reduction:**

   This project will use both numerical and analytical methods (supported through back-analysis of real mine data / cases) to evaluate the impact of emplacement of in-pit tailings or waste rock above an active cave mine, to reduce cave subsidence growth. This work will include an evaluation of inrush risks associated with the infilling of the subsidence zone.

3. **Alternative Extraction Methods:**

   The expectation is that this project will comprise of a multi-disciplinary team of mining, geotechnical and processing engineers who will investigate the application of a combination of HF and In-situ leaching technologies to extract metals/minerals from late-life mines. The target mines will be those that are known to contain unrecovered ore, such as cave mines containing uncaved ore (underbreaks/overhangs, etc) and/ore diluted ore that is uneconomic to mine using conventional load-haul-dump equipment. The plan is to conduct a mine-scale trial on a prematurely closed cave mine (e.g., Northparkes E26, Northparkes E48 block caves).

3.13 Education

The BRC, through its Deep Mining Geoscience (DMG) group, has developed a 'Cave Mining' professional development programme to complement its existing range of professional development courses, as listed on the SMI website https://smi.uq.edu.au/deep-mining-geoscience

The objective of DMG professional development training is to provide industry professionals with the fundamental, theoretical knowledge and practical technical skills necessary for undertaking caving studies and operating cave mines.

These training modules focus primarily on underground geotechnical engineering, cave geomechanics and cave engineering, though the fundamental topics (e.g. Geotechnical Core Logging and Rock Mass Characterisation) can also be applied to other mining methods.

Cave Mining Fundamentals Course

The objective of the Cave Mining Fundamentals course is to accelerate the learning of engineers and geoscience professionals, particularly those who have no underground and/or cave mining experience.
The course content has been ideally developed for site 'classroom' training but has also been adapted to an online Learning Management System.
The course is subdivided into modules, starting with fundamental rock mass data collection and analysis and then building on these, each module building on learnings and data from preceding modules.

Cave Mining Fundamentals modules:

- *Rock Mass Characterisation*
- *Caveability & Cave Propagation*
- *Cave Subsidence*
- *Cave Fragmentation*
- *Cave Flow & Drawpoint Spacing*
- *Undercut Methods & Design (includes Drill & Blast Design)*
- *Cave Ground Support Design*
- *Cave Management (Draw Control) and Operations*
- *Managing Caving Hazards*

https://smi.uq.edu.au/deep-mining-geoscience

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