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Evolution of undercutting in panel and block caves: from shallow to deep/high-stress environments

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ABSTRACT

As caving operations move to greater depths, the higher stress environment presents a significant challenge, namely the damage to the production level rock mass due to the high abutment stresses induced during undercutting. In an attempt to mitigate against abutment stress damage, a range of undercutting methodologies and undercut design modifications have been developed for cave mines over the past several decades. This paper investigates the evolution of undercutting methods and the primary factors that have driven their design changes over time. Qualitative analysis has been undertaken to explore the key changes/modifications made to reduce the undercut stress-induced damage, reviewing previous and current cave mining experiences. Whilst each caving operation is unique regarding geological and geotechnical conditions, this paper attempts to categorise them based on common trends in undercut design and methodology. The results of this object assessment serve to critique the main technical drivers of undercut design based on industry benchmarking and describe how these drivers are used to effectively manage undercut induced stress deformations.

1 INTRODUCTION

1.1 Undercut definition

The term 'undercut' originally found its use in coal mining, as defined by Fay (1920) as “To cut below or in the lower part of a coal bed by chipping away coal with a pick or mining machine”. Subsequently, this method was adopted in block caving to induce caving, as described by Nelson (1965). In cave mining, an undercut is defined as a horizontal opening (slot or stope) mined to initiate the caving of the deposit in block or panel caves (Hartman, 1987). Laubscher (2000) highlighted that “Undercutting is one of the most important items in cave mining, as, not only is a complete undercut necessary to induce a cave but the design of the undercut and the sequencing of the undercutting also provides a facility to reduce the effects of the induced abutment stress”. Further expounding upon this, Butcher (2000) explained that undercutting aims to initiate caving with minimal damage to the block or panel's draw horizon (extraction level) and the surrounding rock mass. The undercut is located above the extraction level and directly linked to it through drawbells connecting the drawpoints. The undercutting consists of two primary components: the undercut methods (sequence) and its geometrical parameters.

1.2 Undercut methods

The undercutting process can be categorised into two primary methods based on the timing of undercut advance in relation to drawbell development. Their distinction pertains to whether the extraction level excavations and pillars experience high abutment stresses or if they are excavated in a de-stressed environment. These two methods are referred to as post-undercutting and pre-undercutting, respectively. According to Brown (2007), “Early cave mines first used post or conventional undercutting, establishing the draw bells on the extraction level below before blasting the undercut stope above into these drawbells”.

As caving operations delve deeper, the impact of stress-induced damage to the extraction level rock mass due to undercutting abutment stresses has become more pronounced. In response, a variety of undercutting methodologies and parameter adjustments have been developed to mitigate these effects more effectively throughout the long lifespan of block/panel caving operations.

1.3 Undercut geometry

The geometry of undercutting plays a critical role in the design of cave mines, as it directly influences several key aspects of the mining process. Notable geometry impacts include the formation of remnant (unbroken) pillars, high-induced stress concentration, the possibility of 'stacking' of large rocks over the major apex pillar, hang-up management, and production capacity during the undercutting phase. The undercutting geometry comprises several essential elements that significantly affect the integrity of the rock mass. These elements, documented by (Brown, 2007; Darling, 2023; Laubscher et al., 2017), include the following:

- The separation distance between the undercut and extraction level (inter-level spacing)
- Height of the undercut
- Profile of the undercut or ring design
- Shape and orientation of the undercutting face
- The direction of undercut advance and starting point and
- Rate of undercutting

Once undercutting is initiated, stress levels increase in the abutment zone ahead of and beneath the undercut face as a function of the size and geometry of the undercut. Stress levels in the abutment zone can increase to as much as three times the virgin stress (Bartlett & Nesbitt, 2000).

This paper explores the evolution of various undercutting methodologies in block and panel cave operations, charting their progression from shallow and low-stress conditions to deep and high-stress environments over time.

2 METHODOLOGY

2.1 Chronological review and benchmarking

A chronological review of the undercut design and its practical implementation will examine the progressive evolution of undercutting techniques in response to different geotechnical and mining conditions. The effectiveness of the undercutting process hinges upon the interplay between geotechnical parameters and mining geometry. It focuses particularly on examining the challenges linked with these strategies, aiming to understand their direct impact on cave performance. Within this context, the review critically assesses the need for a simple framework to guide the design and execution of undercut methodologies, particularly when applied in deep and high-stress environments. To achieve these goals, the review draws extensively from numerous publications. These papers, technical reports, manuals, and guidelines highlight the nuances of block caving and provide valuable insights based on hard-learned experiences. Furthermore, the review provides valuable insights derived from case studies, describing the changes in undercutting methodologies from both block and panel caving operations.

To better understand how undercutting methods and practices have evolved and adapted to the various challenges encountered in cave environments, a benchmarking study into undercutting practices from past and current block and panel caving operations was undertaken. The benchmarking was structured to gather and analyse relevant data related to various aspects of undercutting, including its types, geometries, and associated performance metrics. This information was collated via an online survey and in-depth interviews with experienced caving engineers. From this benchmarking survey, all undercut design modifications, and the reasons behind them were complied with for all stages of undercutting, so as to understand the evolution of undercutting over time. Using this data, the changes were categorised as a function of their operational depth and stress conditions.

2.2 Shallow to Deep and High-Stress Environments

The definition of deep mining is widely interpreted across different countries, as noted by Potvin et al. (2007), and this definition can differ based on specific underground mining methods. Block caving represents a form of unsupported mass mining and is typically not employed at great depths when compared to supported underground mining methods such as cut and fill or longwall stoping. A similar trend of increasing depths in block and panel caving can be observed across different continents, as illustrated in Figure 1.

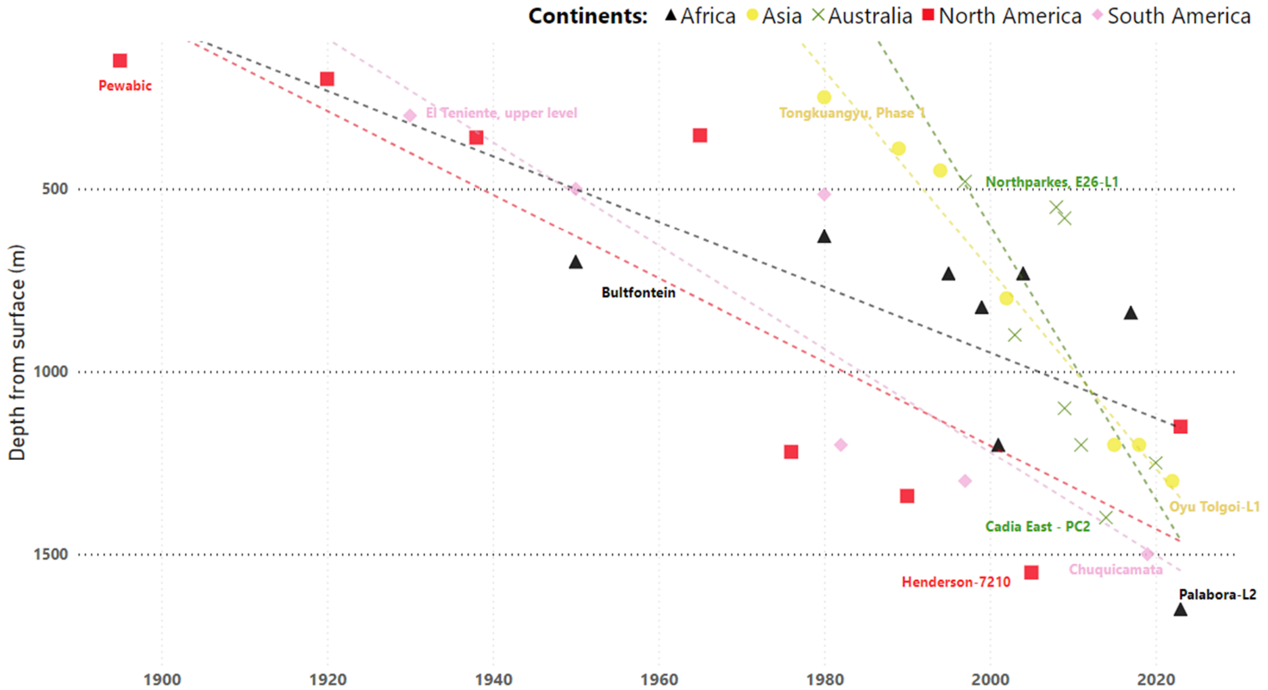

Figure 1 Timeline of operational depths of Block and Panel cave mines by continents, as of 2023, based on various sources, including SME mining engineering handbook series.

The classification of deep mining has evolved over time. According to Miller-Tait et al. (1995) the classification of mining methods designates 'deep mining' of surface and underground operations as those conducted at depths greater than 600 meters below the surface. In their categorisation of appropriate operational depths for various underground mining methods, Hartman and Mutmansky (2002) suggest that typical operational depths for block and panel caving range between 600 meters and 1200 meters; similarly, Laubscher (2011) noted that caving methods are employed at a depths of up to 1500 meters. Suorineni (2017) offers a general classification of mining depths based on challenges in hard rock mining. According to this classification, deep mining refers to depths between 1500-3000m, which encounter significant stress related problems.

Although measuring mining depth is relatively straightforward, simply meters below the surface, categorising a mining operation's stress environment is far more complex. Despite the obvious trend of increasing stress magnitude with depth, the variability of the horizontal stress components is significantly influenced by the prevailing geological conditions, such as major structures or rock mass strength (Potvin et al., 2007). Consequently, it is incorrect to categorise a mine as either deep or high stress based solely on its depth or in situ stress magnitude (Suorineni, 2017). For example, mines that have relatively high-stress magnitudes may encounter minimal stress-related failures if the rock mass is competent. Such mines would typically not be labelled high-stress operations in such cases. Conversely, mines operating within the same stress regime, but which comprise weak rock masses may experience frequent stress-driven failures and challenging mining conditions. These mines should more aptly be classified as high-stress environments (Potvin et al., 2007). Swan et al. (2005) employed a stress-strength ratio to create a graph showing the depths of various deep mines worldwide based on an “overstress” criterion. This criterion is defined as the depth at which the maximum principal stress exceeds the uniaxial compressive strength of the rock. Using a similar approach, the operational stress conditions of various block and panel cave mines can be plotted in terms of depth and stress-strength ratio as presented in Figure 2.

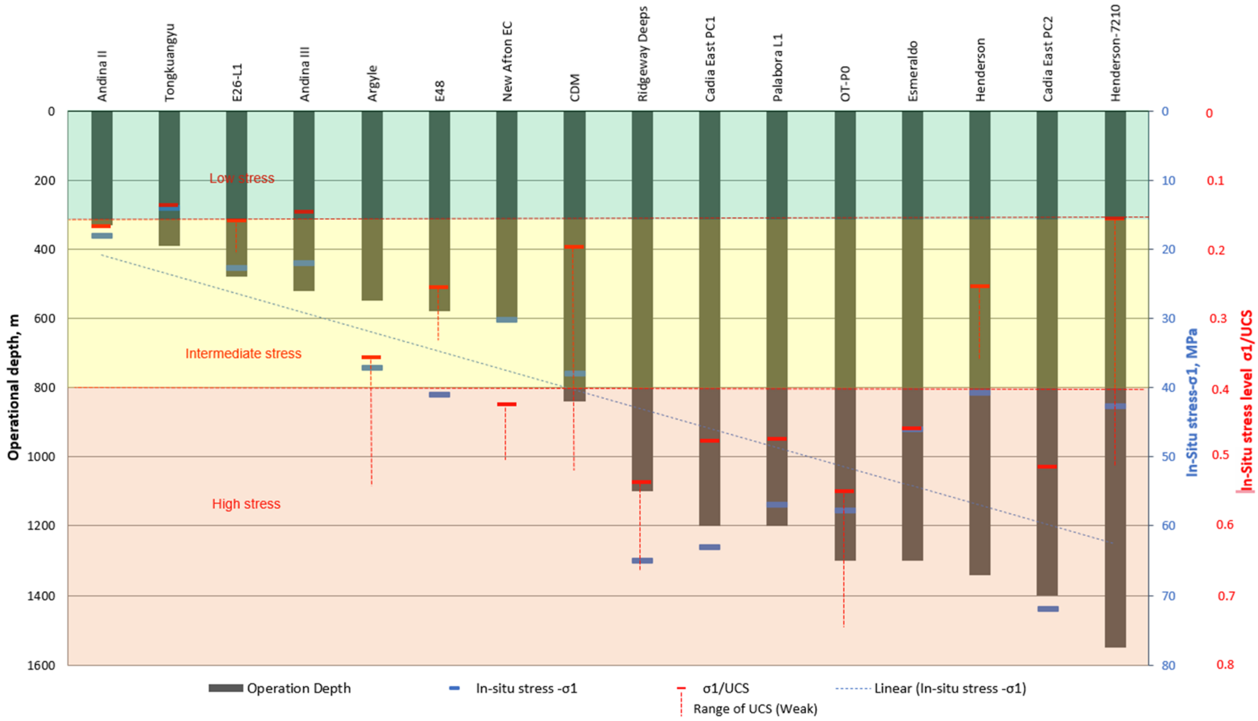

Figure 2 Operational stress conditions of block and panel cave mines.

In general, a clear linear relationship can be observed between operational depths and the maximum horizontal principal stress. In some cases, however, the relatively weak rock mass strength can significantly influence the stress-driven deformations of excavations more so than the operational depth. For example, the Argyle block cave and New Afton’s East and West block cave mines have all operated at relatively shallow depths and yet experienced significant stress-driven deformations; unlike the Henderson mine, which operates at greater depths and yet exhibits lesser deformations, more typical of an intermediate stress environment. It is important to note that the stress magnitude and rock strength values presented in Figure 2 are averages derived from on-site measurements.

3 EVOLUTION OF UNDERCUT METHOD

The evolution of undercut methods over time can be classified into three categories based on operational depths. These categories reflect improvements and adjustments made in response to different mining conditions, as shown in

Figure 3.

Shallow: Early grizzly and slusher system, weight-related issues - undercut geometry modifications

Intermediate depth: LHD system, stress-induced problems - undercut method changes

Deep: High-stress, and wide range of rock mass conditions - Destressing strategy (Advanced or Post-undercutting with pre-conditioning)

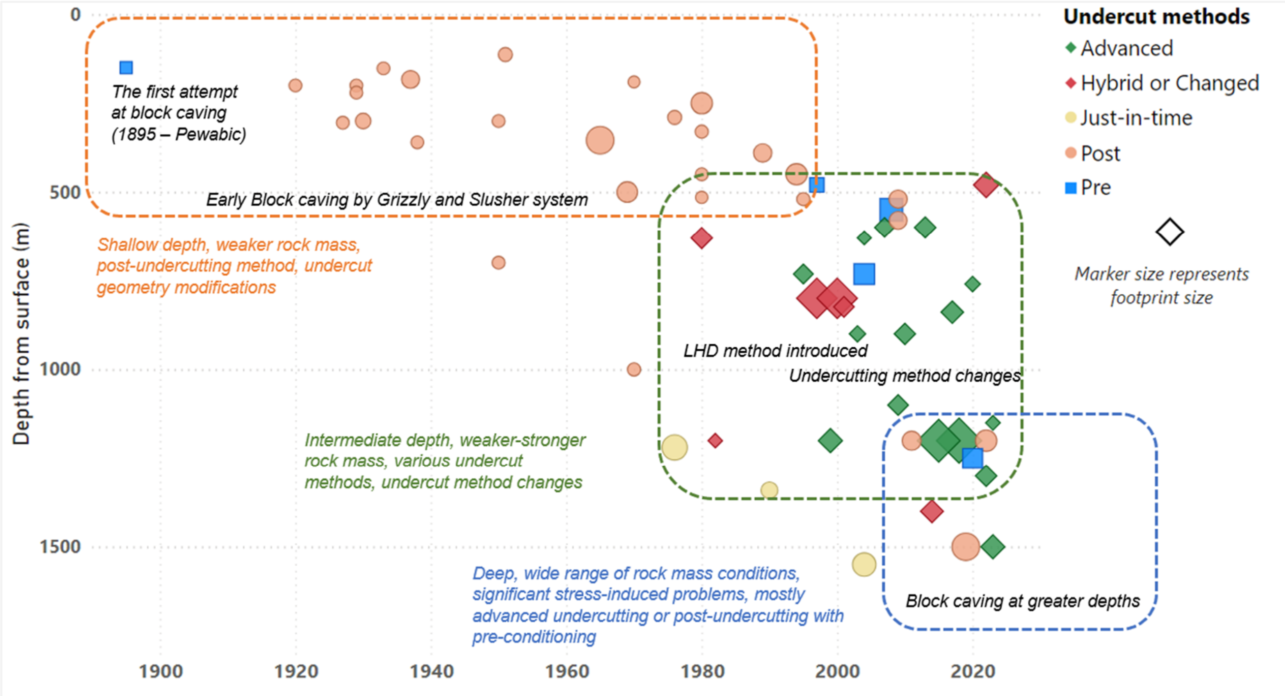

Figure 3 **Application of different undercut methods over time.**

Shallow (<600m): It is worth noting, as described by Bucky (1956), that during the initial attempt at block caving in the Pewabic mine, undercutting took place initially and then crosscuts were developed through crushed rock for draw purposes. In the early stages of block and panel caving operations, the grizzly or slushier extraction system was employed for the material handling system, both of which required the development of inclined raises before the undercutting process. During this period, operational depths remained relatively shallow, typically only reaching down to 600 meters from the surface. In general, only the weak ore bodies were selected for cave mining, and drive (and pillar) dimensions in the undercut and production levels were relatively small. However, this selectivity came with a downside, namely that extraction pillars formed in weaker rock masses is susceptible to deformations due to overburden weight-related problems after undercutting (Lacasse & Legast, 1981). The main design considerations for managing weight-related issues included reducing the drift size, upgrading ground support, and increasing pillar thickness between the undercut and the extraction drifts. For example, at the GBT block cave of Freeport Indonesia, the separation distance between levels was increased from five meters to ten meters in areas of extremely weak ground conditions around the slusher drifts (Ward, 1981). Ideally, a smaller opening requires less support, and minimal support is preferred in the undercut drift, as it ends up being drawn through the drawbells and can cause damage to the materials handling system. Numerous case studies have highlighted the problem of extraction level damage related to overburden weight problems in gravity or slusher block caving operations in which the post-undercutting method was employed, and the extraction level was already developed and exposed to undercutting stresses. Extensive investigations into the causes of severe extraction level damage have identified undercutting type as the primary cause of this instability issue. Notable examples supporting this hypothesis include the study at the Bell mine conducted by Lacasse and Legast (1981) and research at the San Manuel mine by (Stewart, 1981); Zappia (1981). The sequence of undercutting was also identified as a major contributing factor to weighting issues, albeit a challenging one to change. The initial undercut sequence employed a checkerboard pattern, which posed significant weighting problems as it created pillars between blocks. Consequently, the undercut sequence was modified to employ a diagonal retreat, as illustrated in Figure 4.

At the Bell mine, during the initiation of the undercut in the second lift, signs of stress induced deformations were observed in the extraction drifts. Efforts were made to address this issue by installing steel sets and yieldable arches, however these measures proved unsuccessful. The extent of the damage affected as much as 46% of all drives in the second lift. In early 1977, an engineering team investigated the reasons behind the damages associated with the grizzly mining method and to assess its future application at Bell. The results highlighted the importance of adapting the undercut rate to the competence of the rock mass, aligning the orientation of the undercut front with joint directions, and positioning the undercut drives above the major apex pillar.

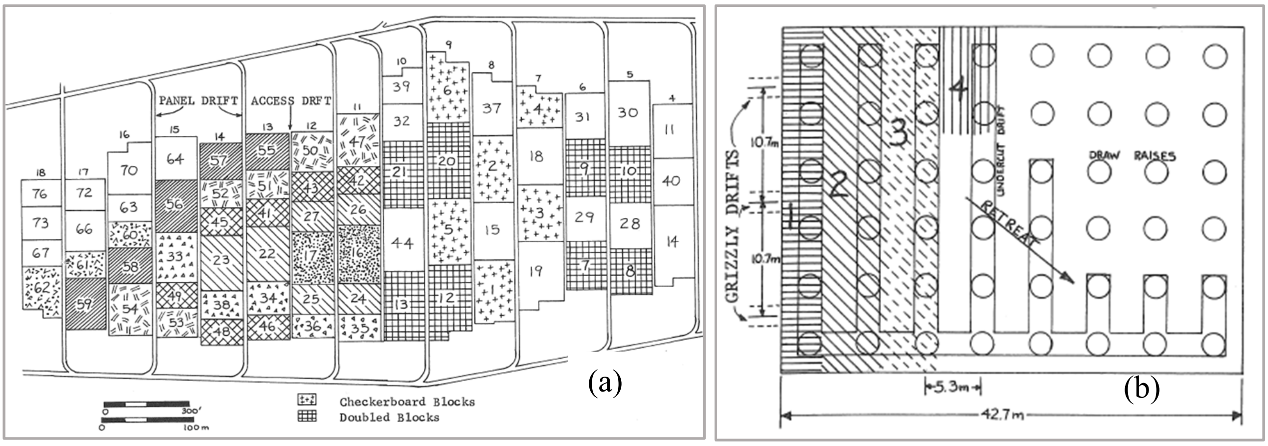

Figure 4 Change of undercut sequence in San Manual Mine (Zappia, 1981), a) checkerboard and b) diagonal undercut face.

Intermediate depth (600-1300m): The introduction of the Load-Haul-Dump (LHD) extraction system into cave mines, in the late 1960s and early 1970s, necessitated the development of larger tunnel (and pillar) sizes to accommodate the new extraction method. As block caving operations progressed to intermediate depths, stress-induced damage on the extraction level due to undercutting abutment stresses became more pronounced, owing to the higher in-situ stress levels. It should be noted that at this time, all caves used the conventional or post-undercutting methodology and hence the extraction level was particularly vulnerable to undercut induced stress damage. To mitigate this problem, the Henderson Mine adopted a different mining sequence, developing the drawbells using long holes drilled from the undercut level. This strategy helped to reduce the duration and magnitude of the abutment stress damage typically associated with post-undercutting (Laubscher, 1994). Whilst this strategy has proved successful, it was not adopted by other caving operations (Laubscher et al., 2017). Post-undercutting was also prevalent in the panel caving operations at El Teniente until the 1980s. However, the significant magnitude of the abutment stresses severely affected the stability of their extraction-level pillars. In addition, several instances of severe rock bursting were observed which were attributed to the high horizontal stresses and local geological features. In response to these challenges, a pre-undercut panel caving method was introduced and tested at El Teniente in 1992. Subsequently, in 1997, this method was implemented on the production level of the new Esmeralda section on the El Teniente sub-5 Level and the Teniente 3 Isla section, resulting in successful outcomes (Araneda & Sougarret, 2008; Jofre, 2000). A similar example was observed in Premier Diamond Mine's BA5 block, where the initial plan involved implementing a panel retreat strategy with a post-undercutting sequence. However, as stress levels intensified on both the undercut and extraction levels, the rate of undercutting slowed, resulting in considerable damage to the extraction level shotcrete lining and caused widespread footwall heave. Consequently, a decision was made to transition to an advanced undercut sequence. This approach involved developing and partially supporting the production drift and drawpoint breakaways prior to undercutting overhead (Bartlett & Croll, 2000).

During this period, there was a trend in block cave mines to use advanced undercutting (Butcher, 2000). However, the development of the extraction level still experienced stress-induced problems due to the slow undercut advance rate which was the result of slow drawbell opening rates (Bartlett, 2010).

Ridgeway Deeps Block Cave (RWD BC):

The RWD block cave case study provides a good example of undercutting challenges experienced at intermediate depth. RWD BC was developed and operated by Newcrest Mining Limited mine near Orange, NSW, Australia and was Newcrest's first Block Cave Operation. RWD BC commenced production at a depth of **1114m,** 224 m below the producing sub-level cave (SLC), in December 2008 and was put into care and maintenance in 2016.

The paper by Lett and Capes (2012) outlined the general deposit geology, geotechnical characterisation and cave propagation and subsidence behaviour. RWD and its caving history is an example of the wide variation in the expected and the actual mining response. These differences include cave propagation behaviour, fragmentation, ore recovery, collapse from rock bursting, excavation stability impacts from undercutting rate and sequence changes that were made without consideration of the rock mass response.

Overall, the lessons learnt encompassed the requirement to collect sufficient geotechnical and structural geological data during the early phases of mining so that suitable knowledge is ready to be utilised during undercutting and cave propagation. The learnings were applied directly to the following stages, mine development, cave establishment, cave propagation, cave breakthrough and steady state production. Additionally, the use of Trigger Response Plans can be utilised to act early enough to rectify or mitigate from 'High Impact' events. These events underpin the basis of the role of geotechnical engineers in caving operations and the need to utilise Major Hazard Management Plans.

Learnings were also captured about two geotechnical events, a large seismic event that impacted the undercut and rapid caving resulting in ore sterilisation risks are described in this paper.

RWD was developed as an Advanced Undercut and was initiated in the northeast corner of the footprint and progressed towards the southwest corner after Capes et al. (2012) Figure 5.

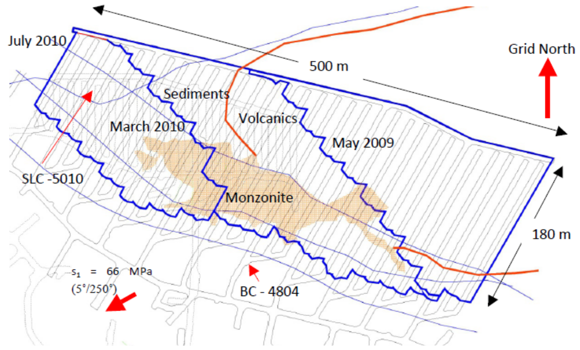

Figure 5 RWD Undercut footprint showing geotechnical domains and selected advance face positions from Capes et al. (2012).

This orientated the undercut front perpendicular to the major principal stress and was the preferred option of the feasibility study to prevent early physical cave interaction to the sublevel-cave through the weaker western fractured sediments aiming to prevent ore recovery risks.

Despite the designed initiation point of the undercut, the cave propagated rapidly along a major structure causing a shrinking pillar to form between the Block Cave and the overlying SLC resulting in a large seismic event that damaged the undercut, refer to Figure 6.

In September 2009 a large damaging seismic event occurred as the undercut passed under the eastern side of the SLC, refer to Figure 7, resulting in months of delay as the site increased the ground support, rescheduled the undercut sequence, and planned a custom draw strategy to recover the south-eastern and north-western areas of the ore body. Refer to Figure 8 for photo of impacted area on undercut.

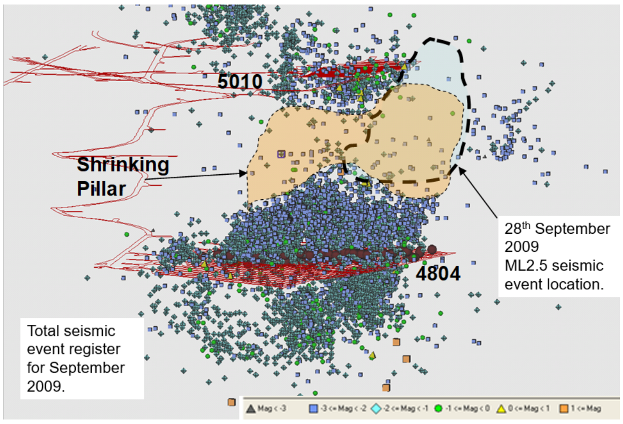

Figure 6 RWD section viewing North showing seismicity for September 2009 and location of large seismic event and SLC with shrinking pillar.

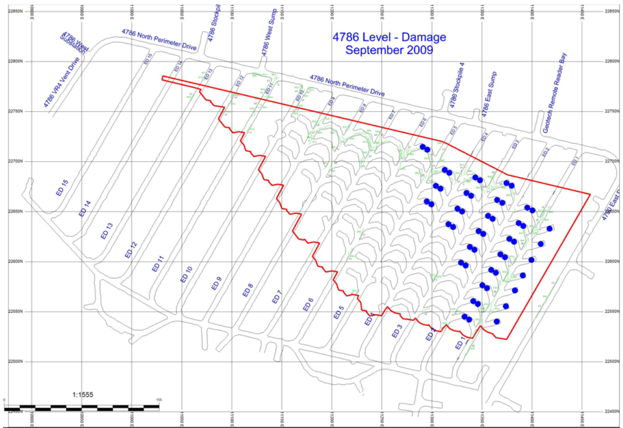

Figure 7 RWD extraction level layout illustrating position of draw bells (blue) and undercut outline (red) and observed rock mass damage (green).

The mine sequencing had allowed the undercut to advance beyond the schedule of the draw bells (i.e. a large veranda formed), in efforts to ramp up to production, refer to Figure 7 which illustrates the draw bell in red and the undercut position in blue for September 2009. The impact of the veranda was only appreciated after the large seismic event and from back-analysis using Flac 2D numerical modelling.

The impact of the undercut position caused a decoupling effect and allowed a large undercut veranda to develop, which in turn developed a large seismic active volume. The increase in overall mine deformation was observed on the undercut level and is summarised in Capes et al. (2012) in

Figure 9.

Figure 8 RWD undercut drive after September seismic event showing scarp of Red Fault and splay in foreground.

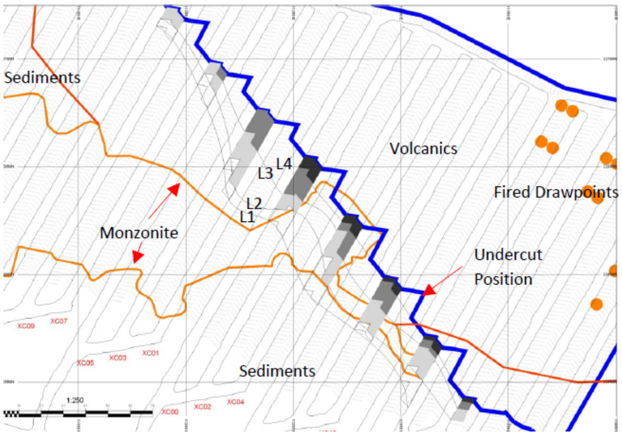

Figure 9 RWD undercut level layout illustrating position of undercut outline (blue), observed damage mapping and geological units after Capes et al. (2012).

The undercut front was progressing towards the high strength and stiff unit of Monzonite and up to 70m of damage was being observed on the undercut drives as the volcanics were being stressed with the large veranda front.

The Red Fault and a splay were later observed by the author to have slipped in the September 2009 seismic event. The investigation posts the event found that the Red Fault was not included in the mine planning process and its impact on undercut stability could have been evaluated.

After the large seismic event and the rapid caving to the SLC, the mine plan was revaluated and a new strategy was put into place, this required the draw bell sequence be caught up to the undercut, refer to

Figure 10, to ensure the full footprint could be produced from to ensure the ore sterilisation impact was mitigated with a customised draw strategy, refer to Figure 11.

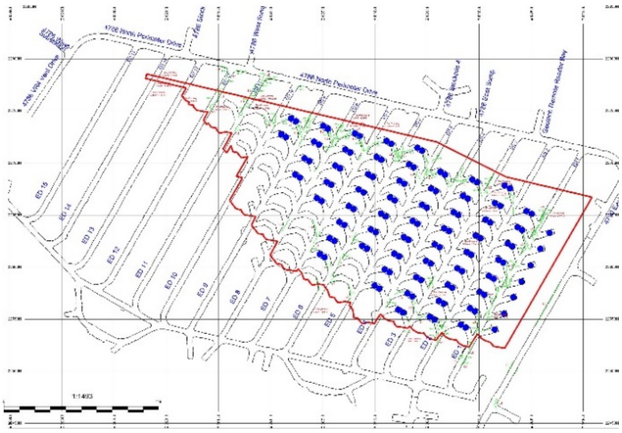

Figure 10 RWD extraction level illustrating post seismic event draw bell availability.

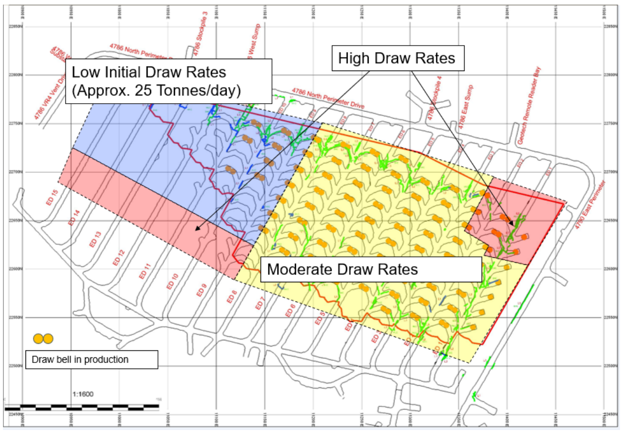

Figure 11 RWD draw strategy to enable recovery of pendants at risk of sterilisation.

A custom draw strategy was created to draw from the eastern half of cave to achieve stress breakthrough and remove the fault-slip hazard by moving the slip area further away from the working area. More data collection was required that included convergence monitoring and a higher resolution geological model to assist with seismic hazard management.

In summary, RWD was challenged by several high impact events that without the technical direction of the geotechnical team and established processes to arrest future risk, the successful production years at RWD would not have followed. The development of the cave through rigorous draw compliance that has recovered the Eastern, southern, and western sections of the cave.

The following list include some of the geotechnical aspects that were encountered at RWD and most, if not all, commenced with cave establishment and during the development of the undercut.

- Geological structures not mapped and not included on plans.
- Lead lags were large and adjacent to volcanic and monzonite contact, large deformations observed as strain was concentrated between undercut face and monzonite.
- Undercut rate and decoupling of draw bell and undercut sequencing allowed seismic hazard to concentrate on Red Fault causing fault-slip event.
- Large event induced by shrinking pillar when UC is passing under SLC.
- Creating large active volume, rapid caving up structures to intersect SLC.
- Customised draw plan recovered large pendants of ore that were not initially caved with seismogenic zone growth.

Deep (> 1300m): As block caving operations moved to greater depths and higher stress conditions, rockbursting became a widespread concern. Several block caving operations that employed the conventional (post)undercutting method encountered significant damage and excessive rehabilitation on the extraction level (Laubscher et al., 2017). Examples of cave mines transitioning from post to advanced undercutting methods, in an effort to mitigate against excessive damage and reduce rockbursting problems, include Freeport's Deep Ore Zone (DOZ) mine in 2002 (Casten et al.,

2002) and Cadia East's PC2 in 2015 (Orrego et al., 2020). The advanced undercutting method is currently widely employed as an effective strategy in managing the undercut abutment stress induce damage on the extraction level, particularly in deep block/panel caves and where the rock mass strength is weak. However, to accelerate the development schedule, fast track cave production and minimise the interplay between cave preparation activities (such as undercut and extraction level development) and those linked to production, some operations have moved away from advanced undercutting and returned to post-undercutting, with rock mass pre-conditioning implemented to mitigate against rockbursting. For example, the El Teniente Esmeralda sector reverted from advanced to post-undercutting methods as a result of operational and stability challenges. These challenges primarily included difficulties in managing a large cave front (>700m) parallel to major structures, which led to fault activation and increased abutment stress. Additionally, operational issues such as veranda length exceeding typical standard and deficient blasting resulted in excessive undercut and extraction level damage (Pardo Mella, 2015). Several authors claim that post-undercutting approach reduces the overall duration required for cave establishment, and enhances efficiency in the process (Flores, 2014).

Cadia East Panel Cave-2 (CE PC2):

The Cadia East (PC2) cave is a good example of a deep cave that modified the undercut method during operations. Cadia East developed the PC2 footprint from 2014 at 1400m depth with 16 extraction drives and employed the post-undercut method. The footprint includes 330 drawpoints with an undercut footprint size of 240m wide and 515m length (123,600m2). The extraction layout is an El Teniente design and includes two Jaw Gyratory crushers.

The PC2 undercut initiation point was subject to rigorous numerical analysis to mitigate both early cave interaction to PC1 and ensure smooth PC2 caveability. Caving on the western side of PC2 would have interacted early with PC1 production and hence a centre position on the footprint for the initiation point was chosen. A large amount of engineering and planning for the cave was based on numerical modelling and aimed to optimise undercut geometry, stress and caveability etc.

Funding for the project was delayed in 2014 for 9 months which caused a pause on cave establishment activities for the eastern side of PC2. Additionally, the level was 12-18 months behind PC1 cave interaction as per the Feasibility schedule which was designed to have PC1 and PC2 caves join to connect to surface as a single cave (CE, 2010).

A large damaging seismic event occurred in February 2015. The event was classified as a pillar crush style event of magnitude 2.1. At the time of the incident the crusher was 1 week from commissioning. The event occurred on the south-eastern side of the undercut footprint and damaged 5,000m2 of extraction drives and draw bell drives, refer to Figure 12 below. The event exposed 6 persons in the area who were undertaking planned ground support works.

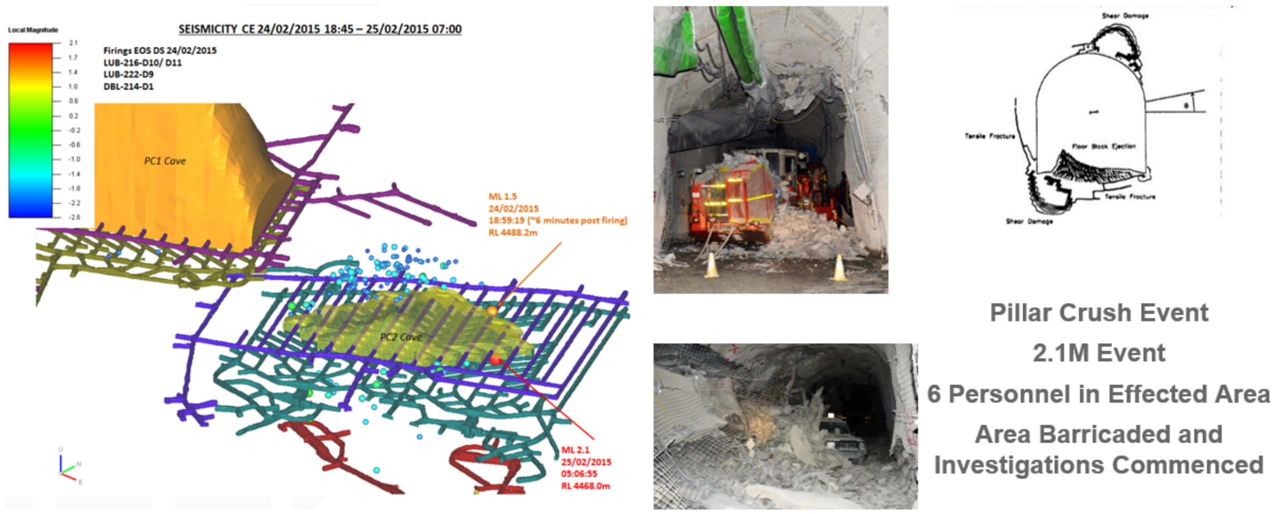

Figure 12 PC2 seismic event February 2015, location of event, cave geometry and photos from incident scene.

Several operational decisions were found to contribute to the root causes of the event, these including:

- Material movement was slowed in the South-East Undercut front from delayed project funding.
- The south-eastern undercut front was parallel to the drawbell drives, causing stress to impact the pillars.
- Development was approved to pre-excavate leading extraction drives in the south-eastern footprint which increased the extraction ratio and reducing pillar size.
- Numerical modelling did not provide a time dependency to failure.
- The plan evolved and changes were made without understanding the impact and without rigorous management of change processes.
- After the incident the company didn't restart cave establishment until it was as safe as possible. This process took 6 months to achieve.

Post incident restart included establishing which sides of the remaining undercut were safe to continue with Post Undercut and which sides required converting to Advanced Undercut in order to manage stress, Figure 13 illustrates the varying areas.

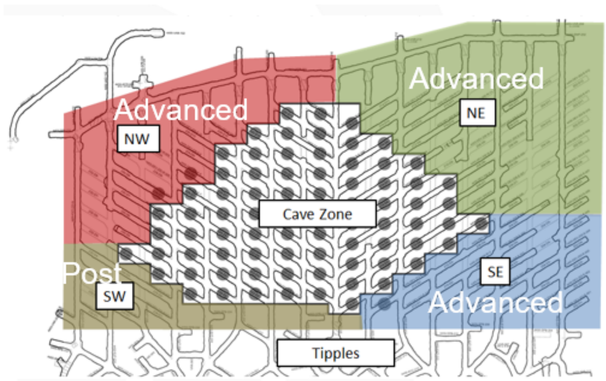

Figure 13 PC2 undercut footprint with different undercut methodologies as per restart in September 2015.

The site changed the undercut method, toughened its ground reinforcement and support elements, changed the way it operated and continued to change only when the change is assessed for safety implications.

The Management of Change process was applied to both ground support upgrades that included installing additional dynamic reinforcement and drilling new undercut rings to allow the areas as per Figure 13 above to be converted to advanced undercut.

The design was challenging because the undercut had been being developed with-out an additional undercut drive above the drawbells, refer to Figure 14 below for a design of the Post to Advanced Undercut design.

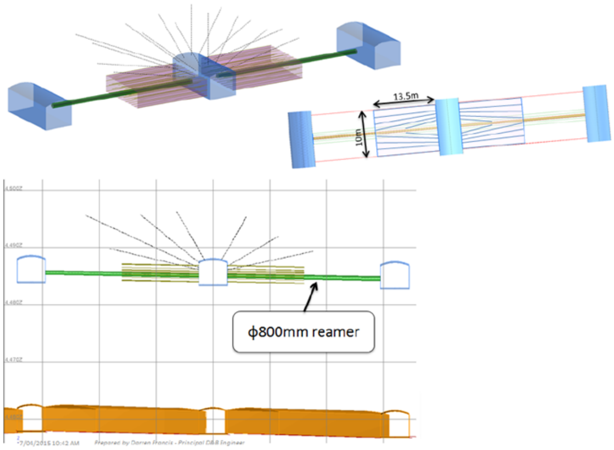

Figure 14 PC2 Advanced Undercut design.

The PC2 footprint was successfully commissioned into full production in December 2016 without any further seismic related issues attributed to undercutting.

4 EVOLUTION OF UNDERCUT PROFILE

A wide range of undercut profiles have found application in different block and panel caving operations. An assessment of these profiles revealed that they are influenced by various geotechnical factors and drilling and blasting techniques, and also depend upon the specific extraction system employed. Historically, earlier cave mines adopted grizzly and slusher systems on the extraction level where undercut designs predominantly utilised fan (full ring), flat, or inclined blasthole configurations (Figure 15).

The undercuts profiles adopted in early cave mines had slightly undulating or flat roofs and floors, with the major apices being rectangular and flat in shape (Brown, 2007). Efforts to enhance ore flow prompted the implementation of inclined drawbell sides, effectively reducing the undercut's floor area. Subsequently, a chevron-shaped or inclined undercut design emerged by inclining the roof and floor.

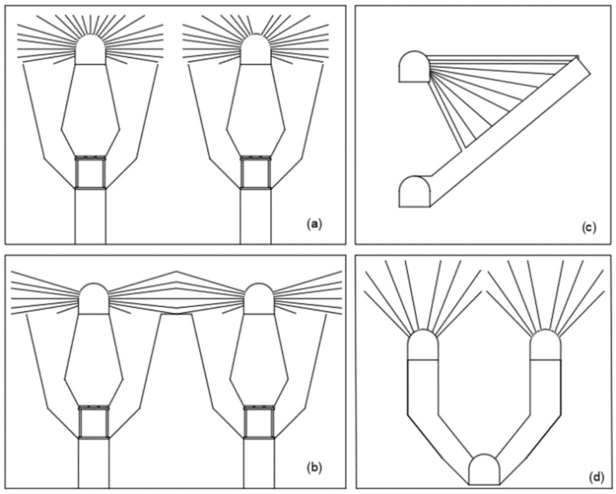

Figure 15 Undercut profiles in Grizzly system: a full ring (a) and flat (b) adopted from Chacon et al. (2004), and in Slusher caves: incline (c), and fan (d) adopted from Laubscher et al. (2017).

The 1970s witnessed the introduction of Load-Haul-Dump (LHD) equipment in block caving operations, thereby altering the extraction system, and associated undercut profiles. Early LHD-based extraction methods often employed traditional fan and flat undercut configurations. A common problem arising from the fan profile was the poor breakage at the drillhole toes which often led the formation of remnant pillars just above the major apex between adjacent rings (Laubscher et al., 2017).

Another issue arising from the fan profile is that it requires extensive drilling and charging which affects the undercut advance rate. Efforts to increase the undercut rate have led to various modifications of the ring fan profile. One such successful modification, locally termed the 'Russian' profile, was implemented at the Premier Diamond Mine. Another profile aimed at reducing the amount of drilling is the narrow flat undercut adopted at the El Teniente mine (Figure 16). Unfortunately, the narrow, flat profiles presented several challenges, including difficulty in mucking the blasted material in the leading faces which led to, chock blasting and the formation of remnant pillars, especially above the major apex.

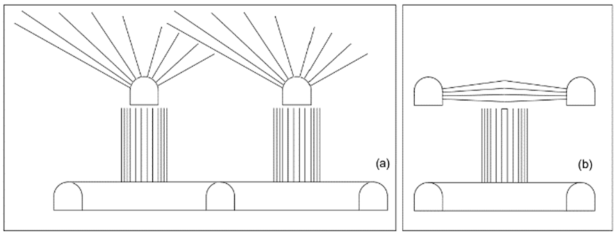

Figure 16 Undercut profiles in LHD system: a Russian (a) and narrow-flat (b) adopted from Laubscher et al. (2017).

Present-day block and panel caves, typically adopt the narrow incline undercut profiles. The underlying rationale involves shaping the major apex to facilitate self-cleaning undercuts that prevent material from stacking above the major apex and mitigates the need for choke blasting (which typically results in poor blasting outcomes and remnant pillar formation).

Deeper and high-stress regimes have prompted modifications to the narrow incline undercut profiles, primarily to reduce the time required for the drilling and blasting process, thereby ensuring that the undercut face advance is fast enough (ideally around 10m/month) to reduce the amount of time that the rock mass is subjected to high abutment stresses. Butcher (2000) also highlighted the preference for narrow undercuts in deep and high-stress environments, given their ability to reduce stress levels by facilitating a quicker undercut advance than the conventional fan rings.

The design of narrow inclined undercuts has undergone several modifications. The most current iteration is known as the ‘Big-W’ undercut, originally proposed by Laubscher (Figure 17). Laubscher proposed that positioning an 'anti-socket' tunnel drive at the primary apex could serve as an observation platform, offering quality assurance of the blast and verifying the breakage of the blast toes, thereby enabling the identification and remediation of remnant pillars prior to firing the next ring. This profile offers several advantages:

1. Enhanced shaping of the major apex, promoting self-cleaning
2. Improved accessibility for inspecting ring blasts and identifying unsuccessful breakage (remnant pillars).
3. Provision of a void for the toe area of undercut ring blasts, reducing the likelihood of chock blasting
4. Opportunity for removing remnant pillars from this level

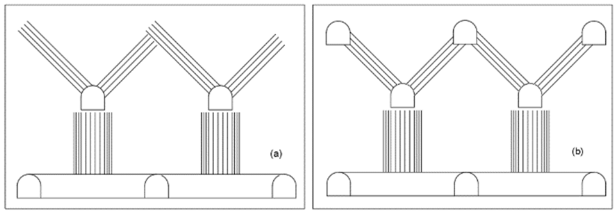

Figure 17 Narrow Incline Undercut profiles in Deep caves: without Apex (a) and with Apex (b) level adopted from (Darling, 2023).

5 EVOLUTION OF GROUND SUPPORTING

Bartlett (1992) highlighted that historically, ground support in cave mining is often based on experience. If a failure occurs, the support levels are increased until the support is sufficient. This trial-and-error approach can lead to major operational problems. As previously mentioned, in shallow cave mines, addressing production level damage during the undercut stage initially involved upgrading ground support systems.

Kendorski et al. (1983) suggested a phased approach to the installation of support in order to overcome support damage during the retreat of the undercutting. In this approach, development or excavation ground support must be upgraded to permanent ground support types based on considerations of structural geology and mining geometry.

As cave mines go deeper and high stress environments, effective ground support becomes a strategic element for successful mine development and uninterrupted production. Kaiser and Moss (2022) introduced a deformation-based ground support design (DBSD) approach which means that if support capacity can be consumed, it can also be restored by preventive support maintenance (PSM). Recent block caves have adopted heavy ground support and PSM approach to maintain both extraction and undercut levels stability during the undercut stage. For instance, at OT P0, the heaviest ground support ever installed in a block cave mine has been used to prevent pillar failure based on previous caving experiences such as Argyle (Stegman et al., 2018).

6 DISCUSSION

There have been numerous cave engineers who have shared their undercutting experiences (successes, failures, and modifications) in block and panel caves. This paper aims to contextualise their findings and apply their hard-learned lessons to deep and high-stress caving environments. The evolution of undercutting over time has seen changes in methods, modifications in geometry, and even changes in the ground support philosophy.

Many operations have successfully transitioned from conventional to advanced undercutting techniques to mitigate stress-induced damage. While advanced undercutting with a narrow-incline profile is preferred in deep and high-stress environments, effective ground support and meticulous scheduling, including strict lead-lag management and improved undercut rates, are important for achieving successful undercutting and less damage to the extraction level.

The production ramp up benefits of post-undercut methods remain attractive and hence it is widely used in deep and high stress environments. Some operations, such as El Teniente and Newcrest, have employed post-undercutting in association with hydraulic fracture rock mass preconditioning, to successfully undercut in highly seismic environments.

Narrow incline rings are now commonplace in caving operations, with recent innovations, including the development of apex levels (Big-W undercut), providing greater stability of the interlevel pillar between the undercut and extraction level. Operations such as New Afton’s East and West caves and Oyu Tolgoi’s Panel 0 cave, have successfully implemented Big-W undercuts with apex levels ensuring complete undercutting.

Further investigation into the successful removal of the apex levels from the Big-W design and the reduction in seismic response due to the application of rock mass pre-conditioning techniques prior to undercutting is warranted.

Another prominent trend that is proving successful in reducing undercutting challenges is the notable enhancement in the intensity and capacity of ground support systems in deep, high-stress environments. Case in point is an illustrative example is evident in Newcrest's RWD cave, where ground support evolved from merely comprising shotcrete and bolts to a system comprising of more dynamic support elements including shotcrete, mesh, debonded bolts, and cable bolts.

7 CONCLUSION

The evolution of undercutting has exhibited distinct changes across different operations over time. Broadly, as caving operations delve deeper into high-stress environments, it becomes apparent that undercut methodologies are progressively customised to address stress-related issues, particularly concerning rock mass damage at the extraction level. This evolution can be categorised into three stages delineated by operational depths, stress conditions, and predominant challenges, as outlined in

Table 1.

Table 1 Evolution of undercutting in block/panel caves

	Periods	Depth	Stress condition	Undercutting challenges	Changes or modifications
I	1895-1960's	Shallow (<600m)	Low	Weak rock mass, weight-related issues on susceptible extraction level	Modifications of undercut geometries and ground supporting
II	1960-2010	Intermediate (600-1300m)	Low to High	Stress induced problem	Different undercut methods
III	2010-Present	Deep (>1300)	High	High-stress, rock burst, excessive deformations	Narrow-incline Advanced undercutting, Pre-conditioning, Heavy (phased) ground support

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