Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)

doi:10.36487/ACG_repo/2465_02

Geotechnical lessons learnt during undercutting in deep caving at Cadia Operations

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Abstract

Cadia Operations (wholly owned by Newmont Mining) initiated block caving with the Ridgeway Deeps block cave (RWD) at depths below 1,000 m in highly stressed conditions using industry leading methods, these practices were extending to the Cadia East orebody. The mine design during the Cadia East pre-feasibility and feasibility study selected panel caving as the preferred method. These initiatives have driven advancements in deep, high-stress underground caving mining. This paper details the development and refinement of advanced and post undercut design methodologies in demanding geotechnical contexts. It assesses performance and geotechnical characteristics, highlighting challenges in cave initiation, undercut sequencing, rock mass response in brittle lithologies, seismic response, ground support performance and geotechnical hazard management. This paper illustrates how advanced and post undercut techniques can be implemented safely with effective risk controls when managing the rock mass response during undercutting. It proposes critical parameters and metrics for an unbiased comparison of these techniques in feasibility studies, aiming to establish a comprehensive checklist for use in the planning phase. This analysis is underpinned by an extensive literature review and benchmarked mine site data.

Keywords: *advanced undercut, post undercut, caveability, core disking, undercut veranda, rock mass response, seismicity, ground support, stress abutment*

1 Introduction

The Ridgeway Deeps (RWD) block cave mine and Cadia East panel caving operation consisting of Panel Cave 1 (PC1-S1), Panel Cave 2 (PC2-S1, PC2-S2 and PC2-S3) and form part of the Cadia Operations (Figures 1 and 2).

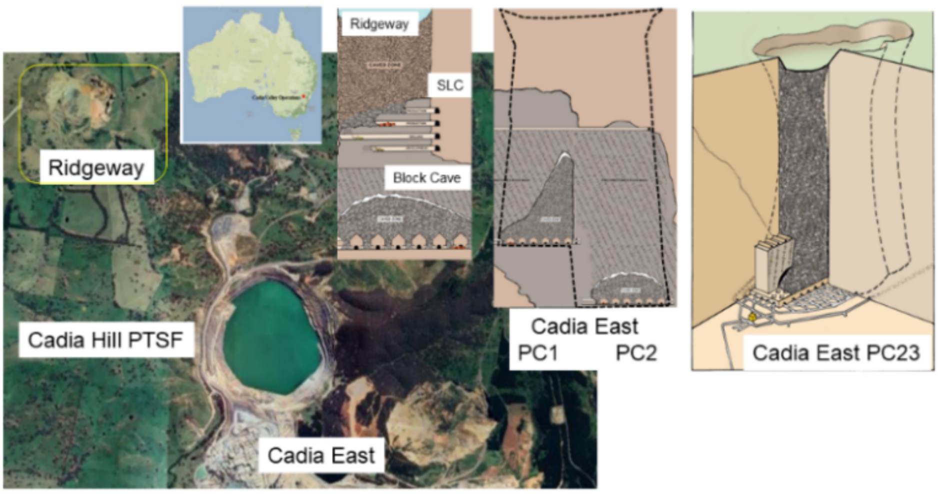

Figure 1 Location of Cadia Operations. Ridgeway Deeps block cave mine, Cadia Hill Open Pit (tailings storage facility) and Cadia East Panel Cave Mines

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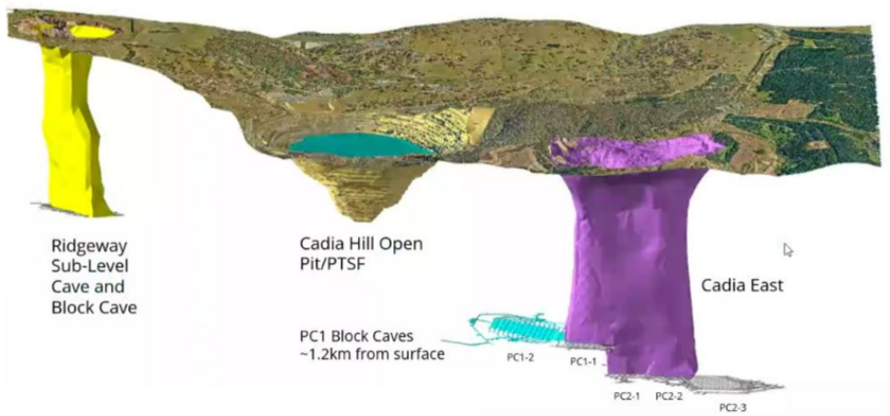


Figure 2 Location of underground caving operations. Ridgeway sublevel cave, block cave, and Cadia East caving operations

Table 1 outlines the key parameters of each mining footprint. Cadia is located approximately 250 km west of Sydney, and 25 km south of Orange, New South Wales, Australia. Each of the mining footprints represent a significant stage in advancing knowledge around cave mining with an evolution of technology and efficiencies gathered with each new caving operation.

Table 1 Cadia Operations, underground mining footprint key parameters

Mine name	Undercut method	Extraction level layout	Undercut area	Footprint depth	Undercut response
Ridgeway Deeps	Advanced	Herringbone	85,000 m²	1,114 m	Rock mass deformation on lithological units/faults. Coarse fragmentation
Cadia East PC1	Hybrid post	El Teniente	73,400 m²	1,200 m	Strainbursting on intrusive contacts, undercut pillar deformation impacting production holes
Cadia East PC2-S1 PC2-S2	Hybrid post converted to advanced	El Teniente	123,600 m²	1,400 m	Brittle rock mass failure Strainbursting on intrusive contacts and rockbursting
Cadia East PC2-S3	Post converted to hybrid post	El Teniente	136,000 m²	1,450 m	Brittle rock mass failure Strainbursting on intrusive contacts and rockbursting

In block caving, the orebody as a block is undercut all at once. Undercutting includes drilling, blasting and removing a layer of the broken rock immediately above an extraction level. This broken rock falls into a pre-constructed series of excavations called drawbells and access tunnels (extraction drives) where loaders collect the ore, it is here that the ore handling process commences. When the undercut material above the extraction level is withdrawn, creating a cavern (the cave), this generates failure of the rock in the void (via stress or gravity) that falls into the cave. The progressive failure and collapse of the periphery rock drives continuous collapse, and the cycle continues. RWD was designed as a block cave.

Panel caving operates on the same principles as block caving but in this variation of the method the orebody or mining block is not undercut completely, but progressively developed as a mining front. Mining takes place in panels/strips some distance behind the undercut face. The cave front length is limited to less than 350 m to minimise overall stress concentration and deformation as it moves across the block or orebody at a constant angle to the direction of advance of the undercut. The advantage of panel caving is that this defers development expenditure. This mining method requires minimal drill and blast, development, and hence operating costs for panel caving are lower than those of other underground mining methods. The application of panel caving is thus a common method for mining large, lower grade orebodies like Cadia East.

Both advanced and post undercutting methods when used at depths over 1,000 m have similar risk of creating large damaging seismic events and deformation during cave establishment, which impacts on the mining schedule and ramp up to production. Damaging seismic events are mitigated using design and operational controls such as:

- preconditioning with hydrofracture
- limiting the overall seismic active volume by using the draw angle concept
- defining stress abutments with management plans
- implementing lead-lags of undercut and drawbells
- scheduling leading and lagging extraction drive development
- installing dynamic ground support
- limiting the length of the undercut front.

These parameters are reviewed in this paper to demonstrate where they are successful, with a few examples provided where they were not implemented and the impact of the outcome explained. The method of undercutting selected is often dependant on geotechnical and engineering properties and requirements. Undercutting is considered one of the most important aspects of a cave (Laubscher 1994) as it will induce caving, but it will also act as an abutment stress shield to the production level. There exists three extensively used undercutting strategies post, pre and advanced undercutting. Each method has its positives and drawbacks leading to new methods or altered hybrid models that incorporate different methods to ensure the best outcome is achieved.

The RWD feasibility study selected advanced undercutting which was initiated in the northeastern corner of the footprint to ensure cave interaction with the sublevel cave (SLC) was delayed and to ensure the remaining SLC tonnes were able to be produced from the lowest levels in the SLC after Lett & Capes 2012. The intended function of the advanced undercut was to initiate caving and shadow the extraction level and drawpoints from abutment stresses and the hazard of rockbursting.

The ground support design included the use of fibrecrete and 2.4 m rockbolts, which was essentially a system with very little dynamic capacity. The advanced undercut sequence in the feasibility design involved the drawpoint and drawbell establishment lagging the undercut front by 60 m. However, during cave establishment this was not followed, and a large undercut veranda and subsequent enlarged seismic active volume formed driving rock mass damage in the undercut; resulting in a large damaging seismic event and rapid cave connection to the SLC above. All the extraction drives were advanced ahead of the undercut front, refer to Figure 3 to illustrate the footprint establishment.

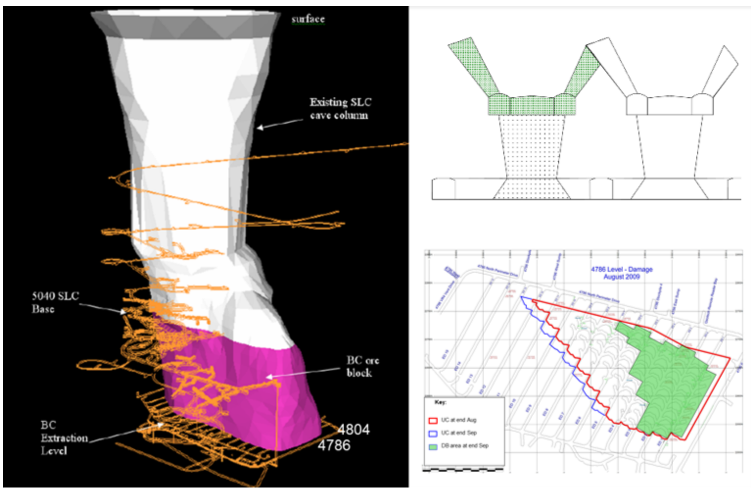
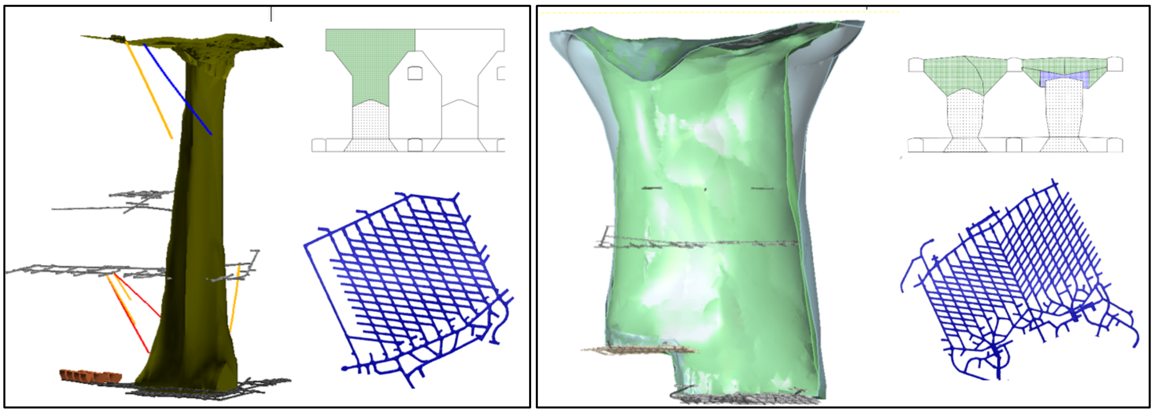


Figure 3 Ridgeway Deeps cave geometry, undercut and major apex design in cross-section and the extraction layout

Cadia East selected a post undercut using a El Teniente extraction layout (Figure 4 and Figure 5) during the feasibility studies (Cadia East 2010) for PC1, PC2 and PC2-3. During the cave establishment activities in 2011, after reviewing several other post undercut operations performances, a change was made to the conventional post undercut design. In PC1 and PC2 the post undercut sequence was altered to lag every second or third extraction drive, this provided a stress shadow for lagged drawbell establishment and larger pillars at the stress abutment and undercut front, that improved the geotechnical stability overall; separating mine development from production activities and saving expenditure on ground support costs without impacting the ramp up schedule.

The change made to the PC1 and PC2 extraction layout that incorporated lagging of extraction drives was called the 'hybrid post' undercut. The hybrid post undercut was implemented across all the footprints where some of the extraction drives and drawbells are developed ahead of the undercut, this created a leading and lagging design. Once the post undercut is fired into an awaiting open drawbell, production can commence and tonnes are available for production earlier for an equivalent period compared to the advanced undercut method. Hence, at Cadia East due to economic reasons, the post undercut is the preferred method. Table 2 outlines key parameters about the Cadia East footprint mining parameters.



(a) (b)

Figure 4 (a) PC1; (b) PC2

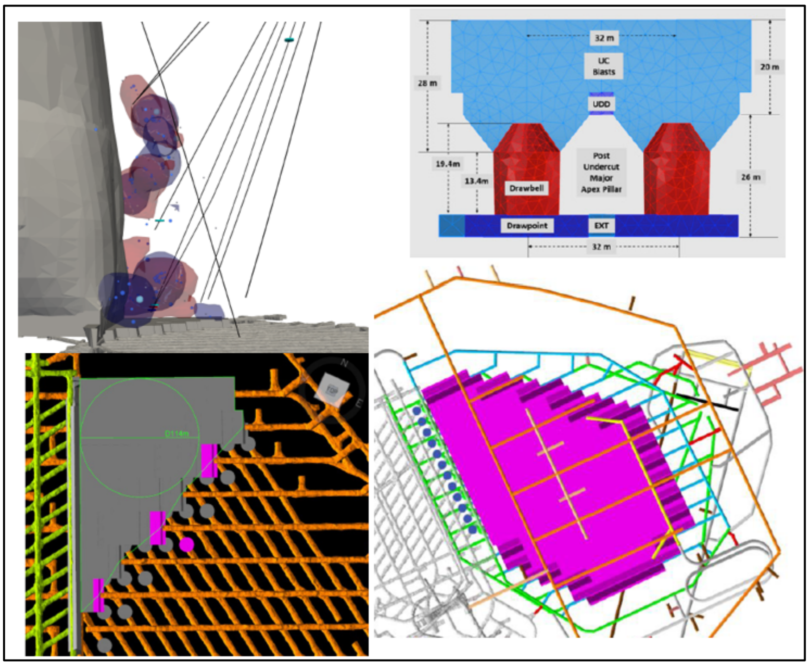
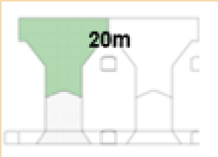
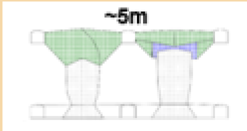
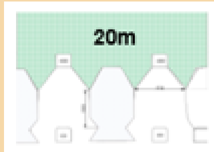


Figure 5 Cadia East PC2-3 extraction layout, cave monitoring array, cross-section of major apex and developed undercut footprint

Table 2 Key mining parameters for Cadia East PC1, PC2 and PC2-3 operations

Factor	PC1	PC2	PC2-3
Undercut height			 
Hydrofracturing	From 45 m above undercut to 5050 galleries. Fractures at 1.5 m spacing	From 60 m above undercut to 5050 galleries. Fractures at 2.0 m spacing	From 40 m above undercut to 5050 galleries. Fractures at 2.0 m spacing Hydrofracturing 40 m above and below extraction level (fracturing through major apex pillars) at 4.0 m spacing
Blast preconditioning (BPC)	254 holes blasted ahead of undercut 165 mm diameter blastholes No blasting in northwest sector due to poor ground	12 trial holes. 165 mm diameter blastholes, same pattern as PC1	4,312 holes planned in Feasibility study, 102 mm diameter Operations optimised undercut height and hydraulic fracturing (HF) to remove BPC in favour of HF
Geology	Lower average rock mass strength than PC2 and PC2-3 High frequency of geological features Host lithology volcanics and monzonite intrusive	Higher average rock mass strength than PC1 and increased silica (brittleness) alteration to eastern side of footprint Moderate frequency of geological features. Host lithology volcanics and monzonite intrusive	Higher average rock mass strength than PC1 and PC2 and increased silica (brittleness) alteration associated with intrusive across footprint Less faults than PC2. Increased localised intrusive dykes Higher percentage volcanic lithology compared to PC2
Secondary break	Non-optimised process Limited data captured for secondary break	Improved process Database collection of secondary break Production based optimisation system improved draw control	Footprint is in cave establishment phase
Production ramp up requirements and drivers	Production rate prioritised over controlled draw strategy.	Improved focus on cave propagation and draw rates. Draw control measures optimised after 2015 seismic event Optimised draw focus on advanced undercut area	Footprint is in cave establishment phase

The PC23 pre-feasibility study selected an advanced undercut as the preferred design, however, during feasibility study a post undercut sequence was approved that involved all the drawpoint drives being established prior to undercutting, while one full drawbell was established ahead of the undercut front (Figure 6 illustrates the footprint establishment). During cave establishment in 2019 an internal site led study was undertaken to increase the size of the drawpoint pillars and reduce pillar stresses during undercutting, every second extraction drive (EXT) drive was advanced ahead of the undercut front, while the alternate EXT drives lagged the undercut front by 40 m as discussed in Orrego et al. 2020.

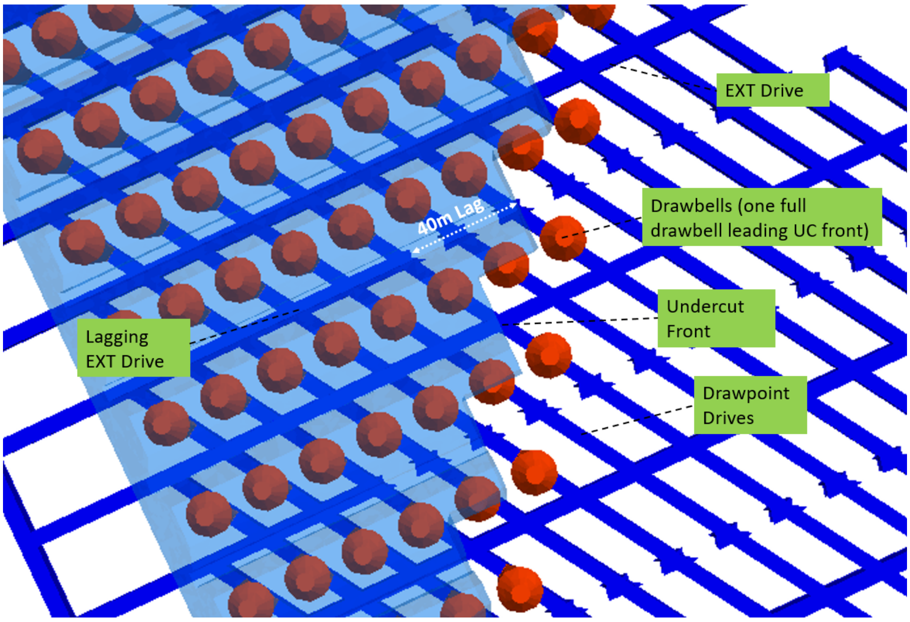
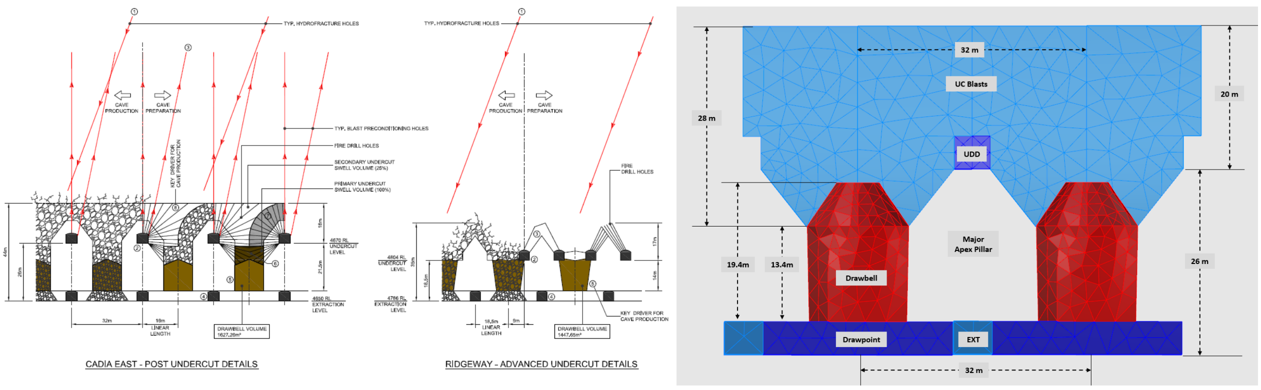


Figure 6 **PC2-3 post undercut lead-lag design where every second EXT drive was advanced ahead of the undercut front, the alternate EXT drives lagged the undercut front by 40 m**

Table 3 and Figure 7 display the comparison between the apex pillar dimensions used at PC1/PC2 and RWD, compared to the PC2-3 pillars (Lett et al. 2016).

Table 3 **Comparison between apex pillars at Cadia (Lett et al. 2016)**

Operation	Major apex pillar	Minor apex pillar (floor to floor)
RWD	30 m	18.5 m
PC1	38.5 m	26 m
PC2	26 m	19.5 m
PC2-3	44 m	22.5 m



(a) (b)

Figure 7 **Section through major apex pillars and comparison between (a) the apex pillar dimensions used at PC1/PC2 and Ridgeway Deeps compared to the (b) PC2-3 pillars (Lett et al. 2016)**

2 Methodology

The methodology discussed presents both advanced and post undercutting methodologies and discusses the geotechnical issues associated with deep and high-stress conditions. This methodology aims to present what factors impact undercutting, and how to plan to minimise outcomes that create major hazards (such as rockburst and collapse) and other operational impacts (such as fragmentation and drawpoint hang-ups).

The evolution of undercut methods over time has been classified by Batkhuu et al. 2024 into three categories based on operational depths, characterised by ranking as shallow, intermediate and deep depths. The categories reflect improvements and adjustments made in response to different mining conditions. Ridgeway and PC1 are classified as intermediate depth (600–1,300 m), where load haul dump systems are utilised, and stress-induced problems have driven undercut method changes. Deep operations (greater than 1,300 m) include increased implementation on automation systems, high stresses in abutments, and a wide range of rock mass conditions. Novel changes to the mine design have been required to re-commence mining, such as the Cadia East PC2 rockburst in 2015, where the post undercut design was required to be changed to advanced undercutting to manage ongoing stresses.

A key drawback of the post undercut method is the higher stresses present in the extraction level during undercutting and the requirement for workers to conduct drawbell charging activities within the stress abutment outside the protection of a machine cabin, is a major exposure to personnel. This exposure to abutment stresses was the main risk evaluated during the pre-feasibility and feasibility studies for Cadia East, for PC1, PC2 and PC2-3. A few key initiatives in reducing personnel exposure for the post undercut method is developing an automated system to charge the drawbells, implementing hydraulic fracturing and installation of robust dynamic support systems. The benefit of the post undercut is that production can commence once the undercut is fired and return on investment can commence almost immediately.

A key advantage of the advanced undercut method is that the drawpoint and drawbell development are constructed after the stress abutment from the undercut front has moved through the rock mass; thus, the extraction, drawbell drives and other long-term excavations will not be subjected to damage from the undercutting front and require less ground support quantities. In comparison, a key weakness of the advanced undercut method is the higher amount of stress interaction between the undercut and extraction levels during undercutting which is observed in RWD.

The information discussed here aims to demonstrate that both advanced and post undercutting methods have equal benefits and challenges and when factors impacting stability or schedule are encountered, issues that impact safe production can occur. For example, with the RWD advanced undercut, due to the undercut veranda established a large seismic active volume was created and deformation in the undercut pillars was driving global mine stability that was part of the mechanism that triggered the large seismic event in September 2009. It was not known at the time that the seismic response of firing the undercut was causing this global seismic hazard as the seismic system didn't have low frequency seismic sensors installed that were required to record low frequency events.

As block caving operations are moving to greater depths and higher stress conditions, rockbursting can become a widespread concern and more precision is needed in seismic systems and analysis in order to allow an understanding in mechanistic drivers to rock mass failure in pillars or the cave back. 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), either due to unexpected stress conditions or where the driving failure is greater than the overall stability of either the pillars in the undercut or extraction level.

Examples of caving operations 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). With advances in preconditioning, cave monitoring and ground support both undercut methodologies offer suitable benefits when implemented and executed well, and when the major hazards are well understood and supported by suitable geotechnical monitoring and analysis.

3 Geotechnical analysis of conditions in advanced and post undercutting at Cadia

3.1 Stress measurements

Characteristics of deep and high-stress conditions at Cadia are defined by stress measurements and damage mapping. Both RWD and Cadia East have extensive data collection methods and systems in place to capture the pre-mining stress conditions using overcoring of Inclusion cells, Australian New Zealand Inflatable Stress Cell (ANZI) and acoustic emission tests, seismic systems that incorporate low and high frequency geophones, displacement instruments and routine damage mapping techniques that track the evolution of the rock mass response to mining. Figure 8 after Lee 2012 demonstrates the extensive stress measurement programs carried out at depth with stress results plotted against depth at RWD and Cadia East.

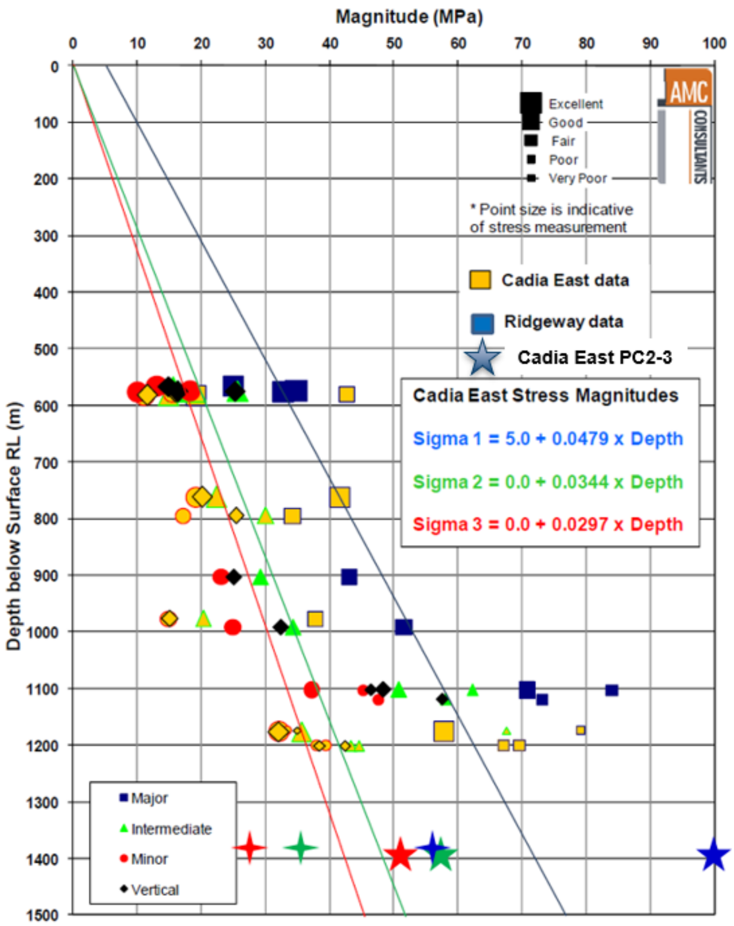


Figure 8 Stress measurement data from Ridgeway Deeps and Cadia East (after Lee 2012)

3.2 Damage mapping of production levels for performance and capacity

Damage mapping at RWD was important to understanding how the production footprint was performing and is discussed by Capes et al. 2012, where during cave establishment, extensive rock mass deformation data was collected on the undercut and subsequently analysed using numerical, analytical and empirical methods. The data consisted of underground observations, convergence (Figure 9) and extensometer measurements, and microseismic data. This information was used to make key tactical decisions during undercutting, in particular mitigating or managing operational impacts relating to deformation, damage and seismicity.

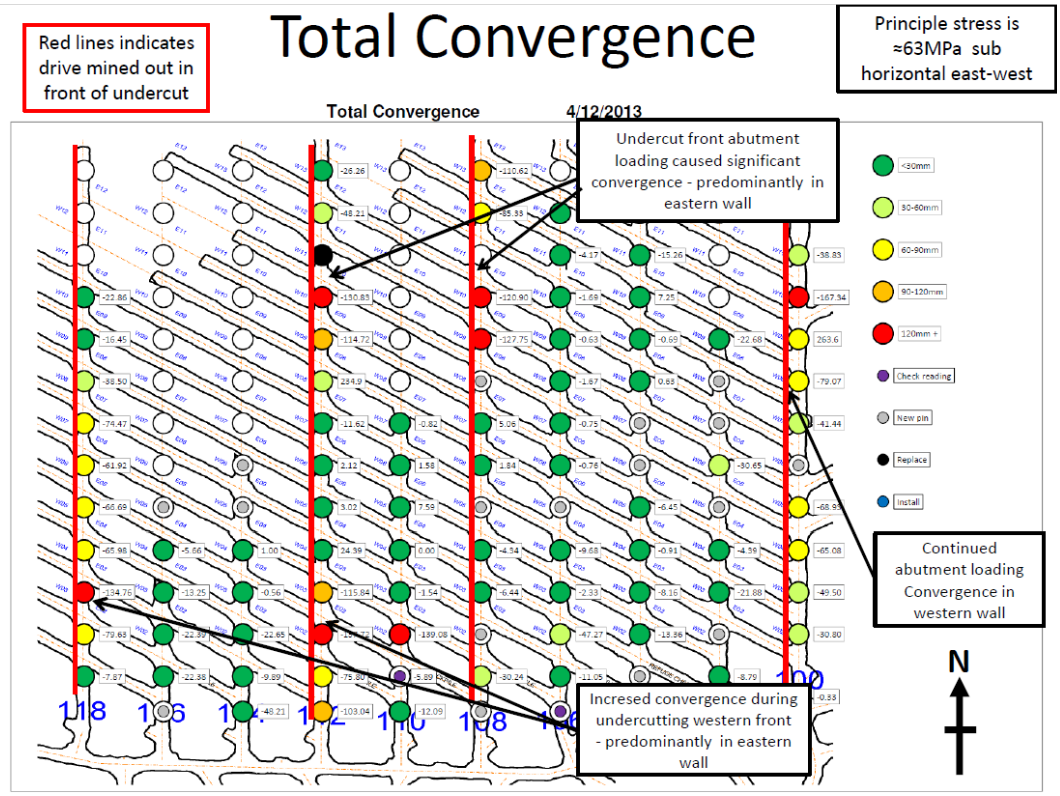


Figure 9 Cadia East PC1 extraction level and total convergence in millimetres recorded during life of the footprint

Cadia East damage mapping systems provided the data and observations needed to evaluate both the performance of the excavation, pillars and the ground support capacity, with the newly established LiDAR technology the operation can assess remaining ground support capacity. Figure 10 shows the LiDAR technology being used to measure the displacement of the ground support system and excavation profile before and after a rockburst in the abutment. The measured results provide an understanding of how much dynamic ground support capacity was used up in the seismic event and what additional rehabilitation is needed to bring the area back to standard.

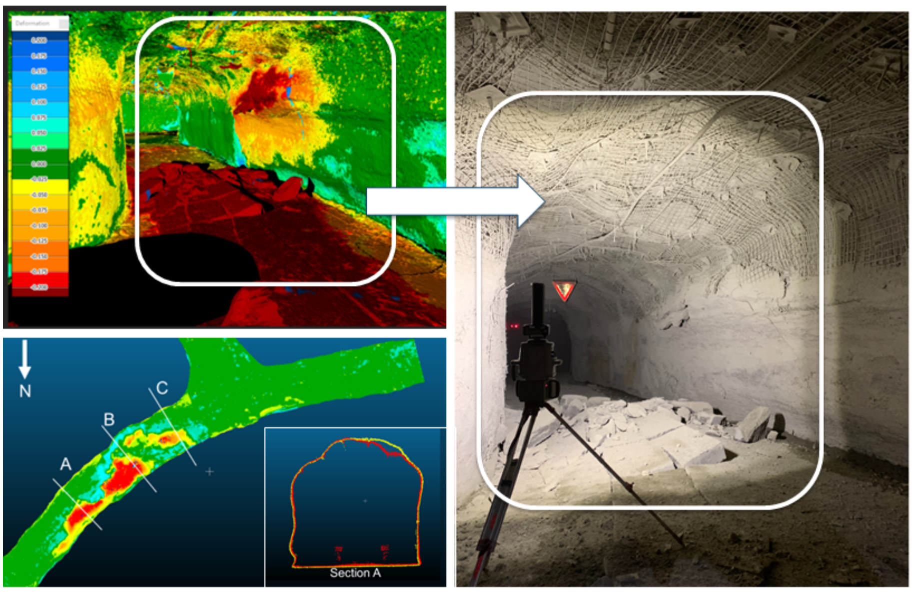


Figure 10 Use of LiDAR in damage mapping, showing displacement of excavation and ground support system after a rockburst event

3.3 Observed behaviour of brittle rock masses

Heterogeneity of the intrusive lithological units and associated geological contacts at Cadia is an important aspect for understanding the rock mass response during the development of new caving operations. The cause of seismicity from stiff rock mass domains is common to both Ridgeway and Cadia East. Prior to stress measurement programs and installation of seismic systems, the occurrence of core disking or strainbursting of development faces, provides the geotechnical engineers the information to identify rock mass domains that will be problematic during all phases of the mine's life. During a drilling campaign in PC1 that was aimed to characterise the structural geology, several diamond drill holes intersected the monzonite and volcanic units at the extraction level depth. These drill holes produced several intervals of core disking occurring on the contact of the monzonite and volcanic unit, this information would provide ongoing hazard awareness to the geotechnical team as seismicity would occur during development and later during undercutting on the same lithological contacts. Additional safety measures were put in place prior to prevent exposure to personnel. Seismicity was recorded on contacts between high strength and brittle units and the impact of the stress abutment caused by the undercut was observed continuously, with some regions requiring barricading when large seismic events occurred (pillar burst or local strainbursting mechanisms) for up to 24 hours during undercut firings.

3.4 Observations of core disking at Cadia East mine

Drillhole MPD593 (UE162A) was collared from the 4645-CCA-1-N (PC1 crusher chamber access) and drilled to the designed 370 m total depth at a dip of −15° to sample the rock mass beneath the PC1 extraction level. The drillhole was drilled prior to cave establishment and before stress measurements and provided an early understanding of the stress state pre-cave establishment. At approximately 160 m the drillcore intersected a contact of volcanics and the monzonite orebody. At 166,065 m core disking was observed for a total of nine intervals, continuing for 9 m within the monzonite orebody. The disking was observed as short (< 25 mm) length sections of solid concave pieces of core, as captured in Figure 11. Jaeger & Cook (1963) first suggested that the spacing and shape of the individual disks could be an indicator of the in situ stress state and direction for the principal stress component. It is assumed that the ratio of the thickness to diameter of the disk decreases as the stress increases and the surface becomes concave. This concave disking has also been observed by Obert & Stephenson (1965), Stacey (1982) and Haimson & Lee (1995).

Figure 11 Core disking in diamond core hole drilled below PC1 where a monzonite contact was intercepted. Analysis of the intervals provided the stress level for the rock

In lieu of available over coring data from the PC1 extraction level horizon a method used to evaluate the approximate in situ stress magnitudes was utilized (Karzulovic, 2008. pers. comm. RWD project with Lett), using the ratio of core disk thickness to diameter and major principle stress, was used to calculate a range of values (plotted in Figure 12) for the major horizontal stress magnitude based upon the available rock strength testing data and the ratio of the thickness to diameter of the disks. The calculated range of major horizontal stress calculated from the VNIMI method is similar to the stress measurement program plotted in Figure 8 after Lee (2012).

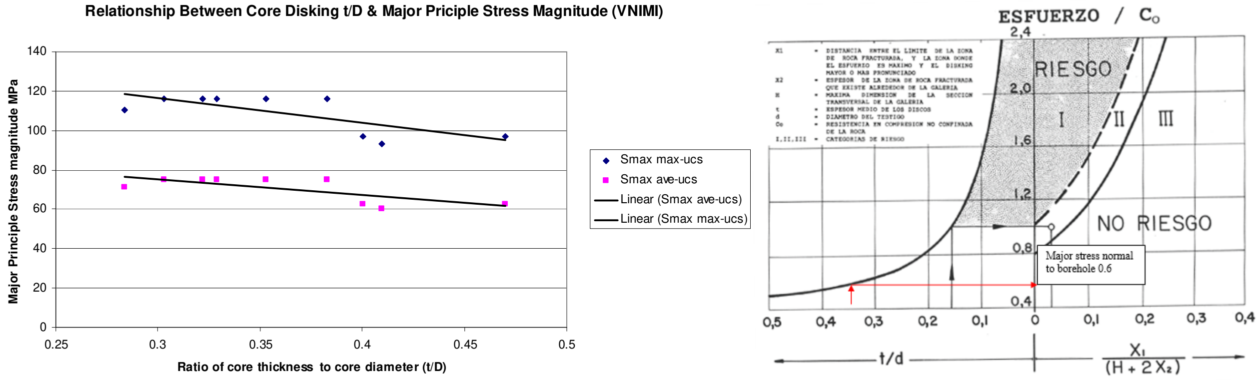


Figure 12 **Plotted results from VNIMI measurement method for UE162A where ratio of core thickness to core diameter provides indicator for major horizontal stress is calculated**

At Ridgeway and Cadia East the contact of the monzonite, volcanic units and porphyry dykes are observed as the main cause of local strainbursting. The stress abutment in the post undercut, recorded larger events where the geometry of the established drawbells and undercut were over a 40 m distance compared to the advanced undercut. This lead-lag distance was captured as a learning from an event in PC1, as illustrated in Figure 13. The mapped monzonite contact was the source of multiple large (implosive mechanisms) seismic events as the undercut was developed across the contact regions. Numerical modelling and an understanding of the mechanisms of the seismic events allowed a customised undercut geometry to be designed and fired, that minimised the seismic response and prevented long-term damage to the major apex and subsequent extraction drive pillars.

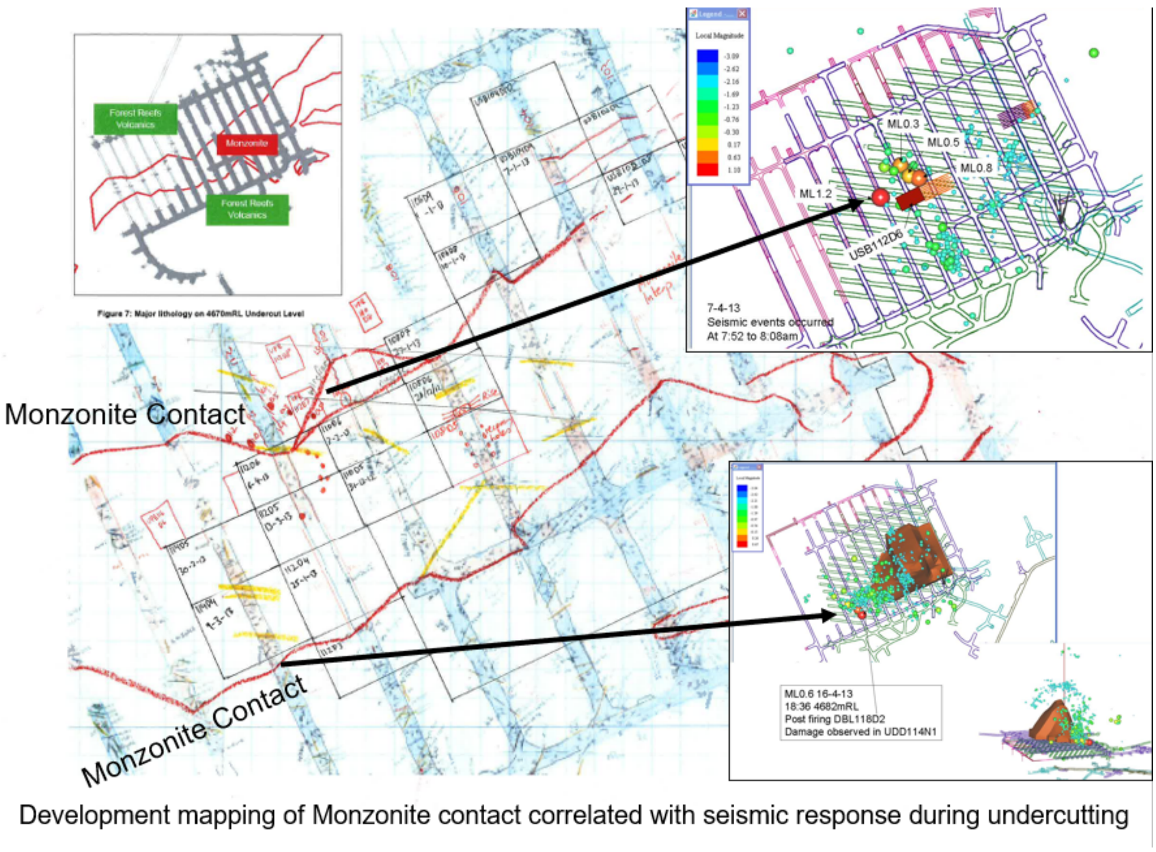


Figure 13 **Cadia East PC1 footprint. Development mapping interpretation of the monzonite and volcanic domains correlating to large seismic event initiated by the undercut firings**

3.5 Stress abutments

The stress abutment at depths greater than 1,200 m at Cadia East, includes all excavations which lie within a 70–85 m zone ahead of the undercut front and 15 m inside the undercut front. The strategic placement of critical infrastructure, such as crusher chambers, needs to consider an extension of the 70–85 m delineation as a larger standoff distance is required. At Cadia East, the standoff distance for critical infrastructure is 110–130 m, depending on elevation, this has been defined from recorded seismic events during caving that were measured at 130 m away from the perimeter of the undercut. Dynamic support installation has also been identified as a requirement to ensure the survivability of the excavation in the event of a large seismic event. Abutment stress zones as per Cuello (2018) are defined based on the following criteria:

- Areas where σ_1: unconfined compressive strength > 0.6 (ratio between maximum principal stress and unconfined uniaxial strength for the intact rock).
- Stresses are likely to increase due to undercutting or cave growth.
- Areas that have higher propensity to experience rockburst, such as geological contacts and faults.

The definition of the PC2-3 abutment is defined from site data and numerical modelling that was calibrated from a large seismic event in PC2 in February 2015, (Figure 14). Where the comparison of major principal stress (Sigma 1) between the PC2 model and the corresponding mining step for the PC2-3 model was compared with a similar sized undercut footprint. Note the maximum Sigma 1 for PC2 and PC2-3 are similar in magnitude, implying that stress conditions for PC2-3 will be similar to that experienced in PC2.

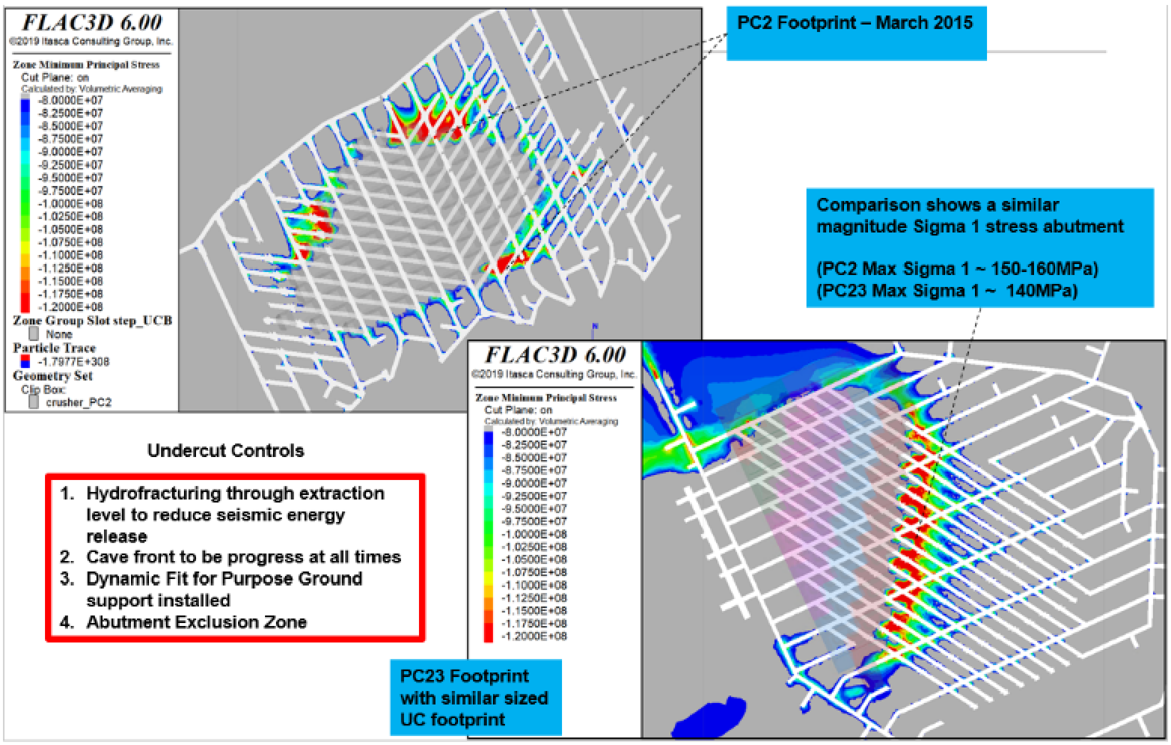
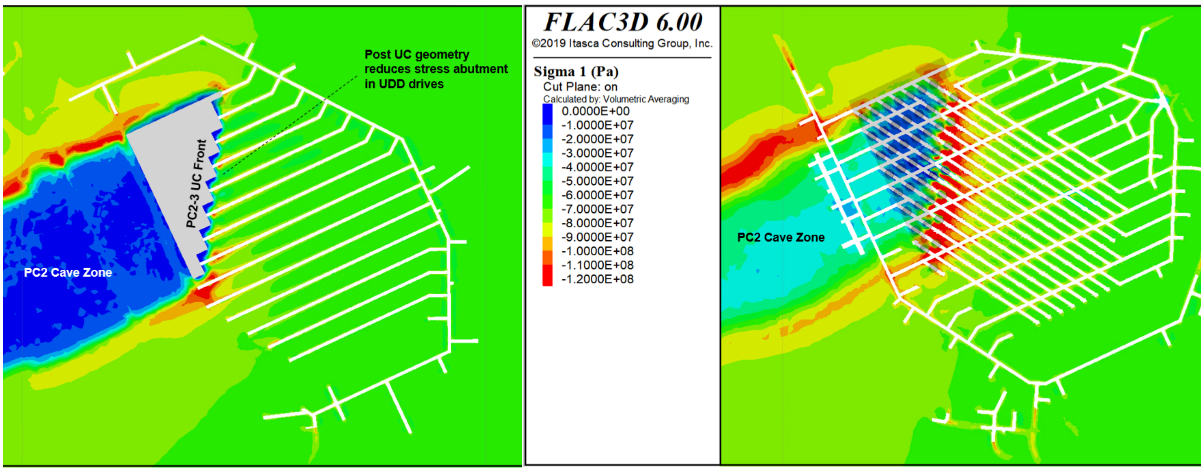


Figure 14 Comparison of major principal stress (Sigma 1) between the PC2 March 2015 calibration model and the corresponding mining step for the PC2-3 model with a similar sized undercut footprint. Note the lagging extraction drives in both footprints ahead of the undercut front

The overall stress conditions and rock mass response for the PC2-3 excavations from initial development to final state cave propagation are modelled to be similar to that experienced in the PC2 operation. Modelled results in Figure 15 show the Sigma 1 stress abutment ahead of the undercutting front for PC2-3, demonstrating that the stress conditions are comparable to PC2; requiring engineered controls such as dynamic ground support and operational procedures such as stress abutment exclusions of over 24hrs for undercut and drawbell firings.



(a) (b)

Figure 15 FLAC3D numerical modelling results from PC2-3 feasibility study illustrating the stress abutment distribution of the PC2 cave and the development of the PC2-3 undercut and stress distribution from the post undercut, note the delayed extraction level drives in (a)

3.6 Concept of lead and lagging extraction drives and production firings

Lead and lagging extraction drives were implemented in PC1 and PC2 to reduce the impact of stress damage on major apex pillars, caused by the stress abutment in a post undercut. By lagging every second or third extraction drive under the undercut, the overall excavation ratio is reduced in the abutment and also reduces overall rock mass damage and rockburst hazard. The size of the extraction level pillars are larger during the cave establishment phase allowing the full development design to be excavated with the lagging extraction level drives under the undercut within a stress shadow. This novel approach has been called the 'hybrid post undercut' and is illustrated in Figure 16.

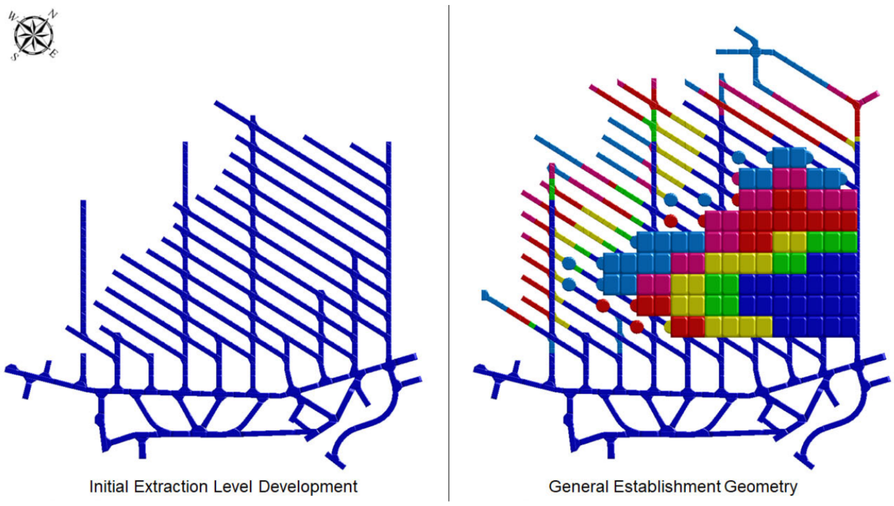


Figure 16 PC1 hybrid post undercut sequence

A comparative numerical modelling analysis was undertaken to show the location and amount of stress and excavation damage created by a true post undercut compared to the hybrid post undercut. The following numerical modelling results are presented for comparison and justify using the hybrid post undercut design, refer to Figures 17 and 18. The numerical model results demonstrate that the stress levels are higher in the stress abutment pillars for the post undercut compared to the equivalent sized hybrid post undercut. The improvement in reducing overall stress distribution is apparent at critical hydraulic radius at approximately 20,000 m² in the hybrid post undercut design. The final stages of undercut and cave establishment have similar levels of stress across both the hybrid and post undercut due to the final position of the cave. These areas are where the final abutment is located and subject to higher stresses, and best managed adequatly with suitable capacity dynamic support in the abutments.

Input parameters for the model includes collected data from PC1 and PC2 and the following findings provide support for executing at depths below 1,200 m.

- The hybrid post extraction layout allows undercut swell to be bogged from drawpoints reducing person to machine interaction risks.
- Reduces upfront development, ground support costs and reduces development congestion.
- The hybrid post undercut had 12.5 MPa lower abutment stresses compared to the traditional post undercut mining geometry.
- The abutment stress and damage increased with undercut footprint size, cave hydraulic radius where damage is visible larger in the traditional post undercut.
- Cumulatively the hybrid post undercut produced lower levels of damage, compared to the traditional post undercut. This is confirmed using a calibrated damage map from the PC1 footprint.
- The hybrid post undercut is superior to the traditional post undercut for limiting stress and damage levels once hydraulic radius has been achieved.

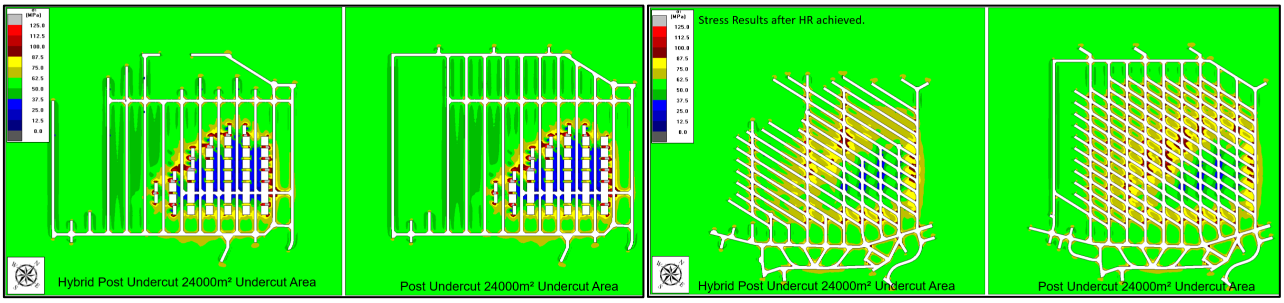


Figure 17 PC1 numerical modelling results for hybrid post undercut and equivalent post undercut plotting Sigma 1 at undercut area 24,000 m². Note that the undercut stress is similar across both the hybrid and post undercut in comparison to the reduced stress in the hybrid post extraction level sections

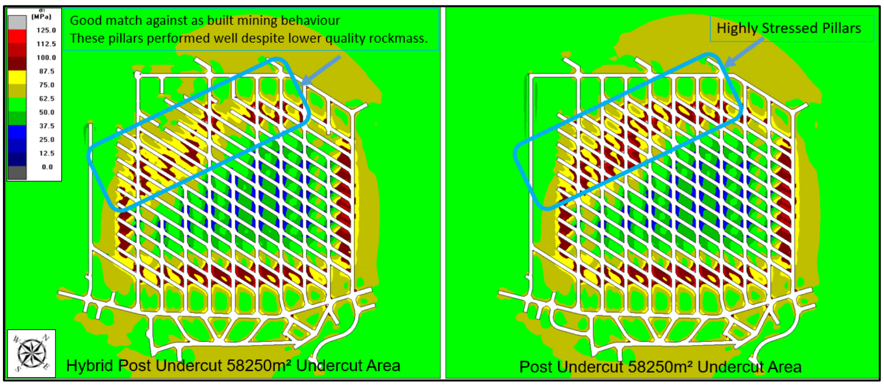


Figure 18 PC1 numerical modelling results for hybrid post undercut and equivalent post undercut plotting Sigma 1 at undercut area 58,250 m². Note that the final abutment stress level is similar across both footprints

The base case for PC2-3 planned cave footprints, as per the pre-feasibility study, is to mine the undercut as an advanced undercut to manage the higher stresses measured around the existing PC2 abutment and to manage the cave establishment activities near the higher stresses of the PC2 cave. The advanced undercut front leads the drawpoint and drawbell development. The lead-lag rules follow a 20–40–60 m rationale by which the drawpoint development cannot be closer than 20 m and not greater than 40 m from the undercut front, while the drawbell development cannot be closer than 40 m and no further away than 60 m from the undercut front. The lead-lag rules for the advanced undercut for PC2-3 are outlined in Table 4 and in section view and Figure 19 displays the lead-lag rules employed at PC2-3 pre-feasibility design.

Table 4 Lead-lag rules for PC2-3 advanced undercut

Undercut level drives	Leads indefinitely
Extraction level drives	Leads indefinitely
Drawpoint development turnouts	Lags by 20 to 40 m (1–2 × drawpoint turnout)
Drawbell establishment	Lags by 40 to 60 m (3–4 × drawbell firings)

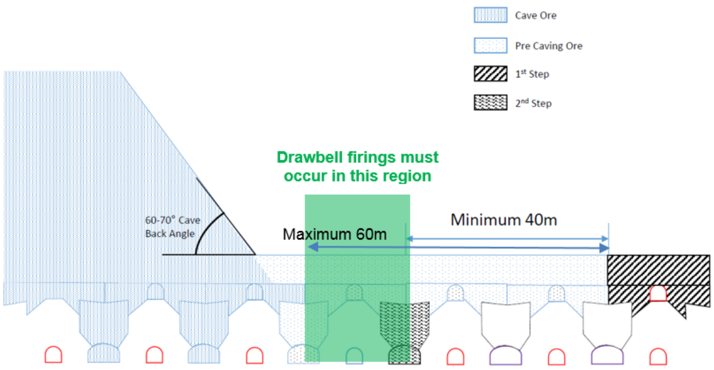


Figure 19 PC2-3 base case advanced undercut section illustrating sequence of undercut and drawbell development

4 Operational case studies

4.1 Cadia East hybrid post undercut

Currently three sectors are in production at Cadia East PC1-S1 at 1,200 m depth and PC2-S1, PC2-S2 and PC2-S3 in development at 1,400 m depth. Commencement of production from Cadia East PC1-S1 cave began in January 2013. Hybrid post undercutting was adopted to establish the cave through to surface, with undercutting retreating from the southeast to northwest direction of the footprint. The total PC1-S1 undercutting area was approximately 73,400 m^2. A total of 218 drawpoints were developed using an El Teniente layout. The PC2 sectors have implemented different variants of the panel caving method (post undercut using the El Teniente layout) and hosted in different rock mass characteristics, stress conditions and depths over 1,400 m.

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 1,400 m depth with 16 extraction drives and employed the hybrid post undercut method. The footprint includes 330 drawpoints with a undercut footprint size of 240 m wide and 515 m length (123,600 m^2). Figure 20 shows how the impact of the post undercut stresses bound between the undercut and extraction level pillars causes rock dislocation in the production holes and shearing to the rockbolts. This occurs as a result of interaction of void from the adjacent drawbell and undercut firings, the section view in Figure 20 illustrates the interaction of the voids and the rock mass damage from numerical modelling. To reduce this rock mass damage and delay to production hole charging, lead-lags were produced over drawbells where there was a lagging extraction drive enabling improved stability where there was limited void and larger pillar volume.

Lagging of the extraction drives was innovated in PC1 to reduce the damage to the extraction drive during the establishment of the post undercut. Every second or third extraction drive was developed ahead of the undercut, based on the geotechnical requirement of reducing the risk of rockbursting and improving the long-term stability of the major apex pillars.

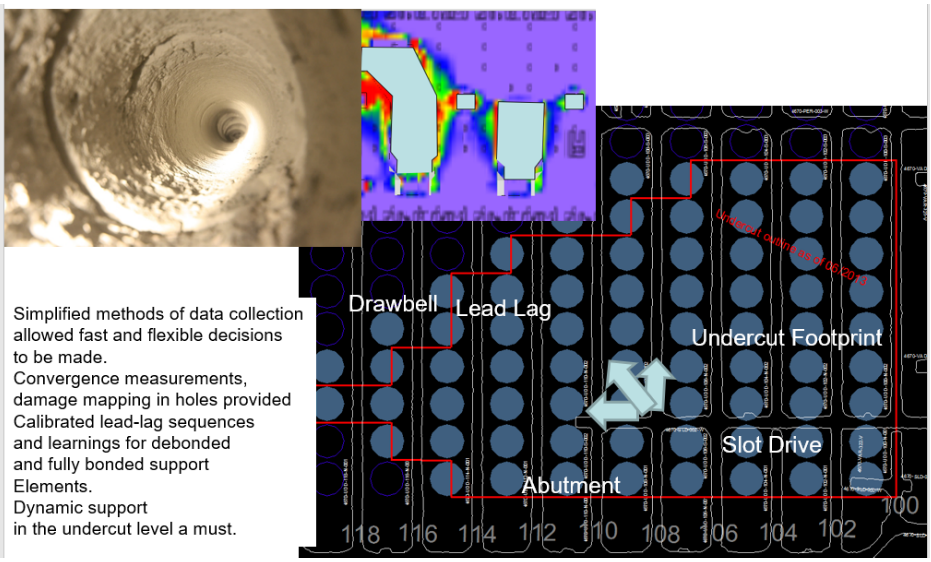


Figure 20 PC1 undercut footprint, typical rock mass damage in production holes and section through numerical model showing impact of void interaction causing rock damage between the undercut and the open drawbell

The major learning from geotechnical monitoring systems on the undercut and extraction levels at Cadia East provided insight into how the major apex pillars, extraction level drives and drawpoints respond to undercutting and caving. The main failure mechanisms experienced can be summarised as rock mass bulking driven by ground deformation (walls and shoulders) and rockbursting located on structures or lithological contacts.

Convergence and deformation in PC1 was limited to pre-mined extraction drives and further damage rendered from undercut lead-lag and drawbell geometries. Once the PC1 undercut and cave footprint approached the caving stage of hydraulic radius (21,500 m²), ground conditions on the extraction level began to show signs of increasing deformation. Deformation trends measured from extraction level instrumentation (convergence pins and extensometers) recorded the effect of the passing post undercut abutment. The data in Figure 21 recorded rock deformation for a leading extraction drive number 8 (EXT108) where total convergence was high.

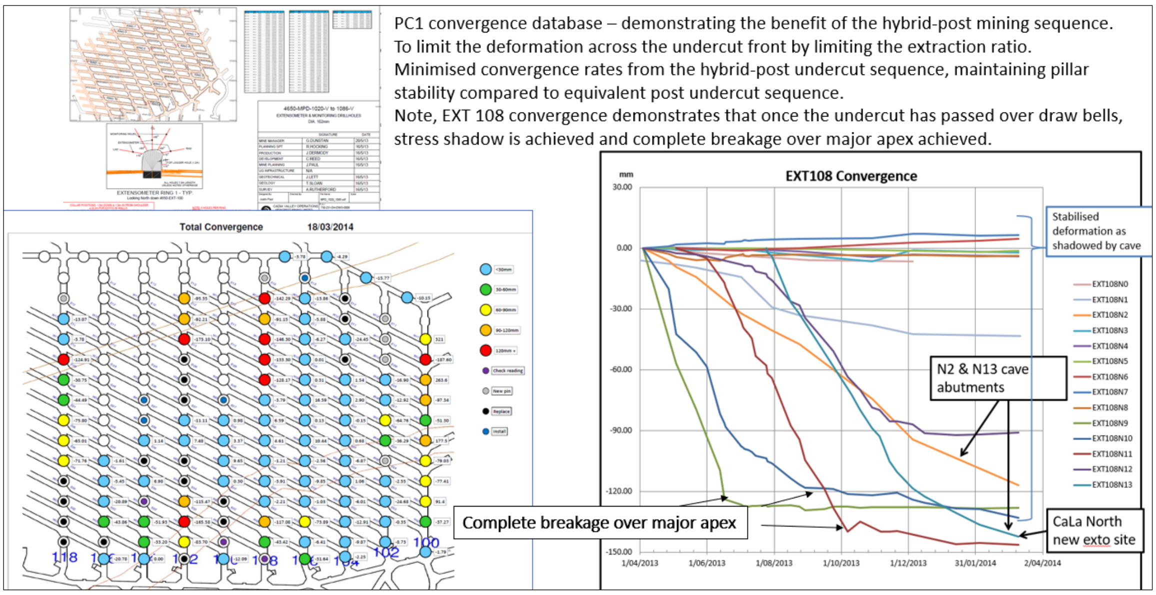


Figure 21 Convergence data from PC1 extraction drive showing impact of cave abutment and leading extraction drive development

The total convergence and stress shadow can be seen in the graph as it flattens once the undercut front had passed over an extraction drive or drawbell. Major deterioration in ground conditions had been experienced where lead-lags were in the excess of 40 m and high extraction ratios existed.

High extraction ratios were observed in all leading extraction drives in PC1 due to multiple drawbells being mined in-front of the undercut front, reducing the overall pillar stability before the undercut passed these areas. Some ground support and reinforcement work was required to return areas to full capacity, to firing undercut or drawbells. The convergence and extensometer data provide insight into how the rock mass responded to the undercutting and seismicity.

4.2 Ridgeway Deeps advanced undercut

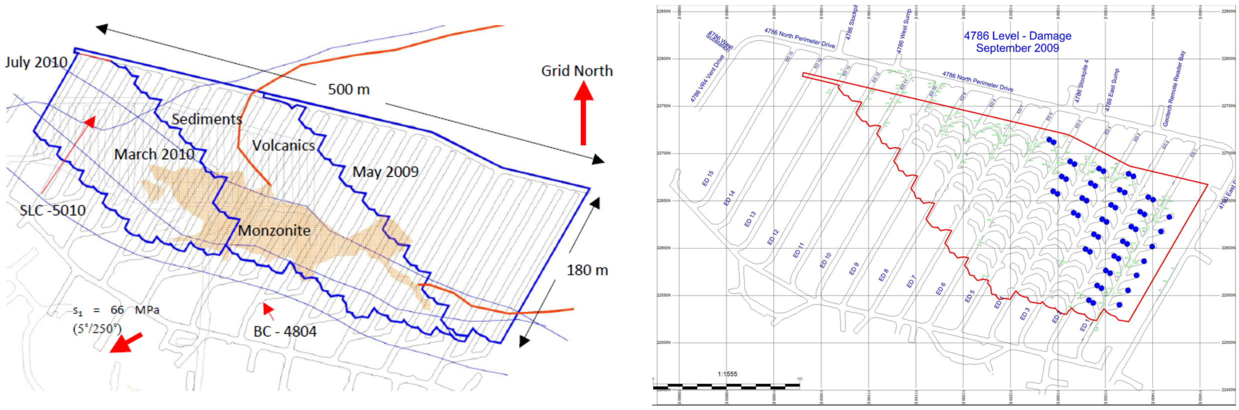
Ridgeway Deeps was designed and executed as an advanced undercut with a herringbone extraction level below the SLC and commenced production at a depth of 1,114 m**,** 224 m below the SLC in December 2008 and was put into care and maintenance in 2016. Lett & Capes (2012) outlined the general deposit geology, geotechnical characterisation and cave propagation and subsidence behaviour.

The RWD block cave case study provides a good example of undercutting challenges experienced at 1,114 m depth in strong and brittle rock mass domains; with complex structural geology. RWD and its undercutting history is an example of the wide variation in mining response. Challenges experienced at RWD include, fragmentation, excavation stability impacts from undercutting rate and sequence changes that drove increased rock mass strain on a major lithological contact that eventually triggered a damaging rockburst event in September 2009. The concept of stress, strain, structure and sequence is in Table 5 and can be applied to RWD to review the overall geotechnical drivers that are used to evaluate stability.

Table 5 Geotechnical drivers for evaluating stability

Stress	Strain	Structure	Sequence
σ_1 66 MPa overall rock mass strength was 120 MPa	Increased due to active volume above and below the undercut Increased as undercut footprint grew and approached monzonite a volcanic/Red Fault Contact	Complex lithological and fault network Unidentified fault that displaced during ML2.5 event	Poor drawbell and undercut sequencing, allowing fast undercutting rate that was not linked to drawbell integration – creating a long veranda and long undercut front

Figure 22a (Capes et al. 2012) illustrates the undercut layout and lithological domains with σ_1 and Figure 22b illustrates the overall undercut position during September 2009, when a large damaging seismic event occurred during an undercut blast; note the position of the drawbells in the northeastern part of the footprint where the undercut was initiated. The undercut face position is far in advance of the drawbells, creating a large undercut veranda.



(a) (b)

Figure 22 After Capes et al (2012): (a) Location of lithological domains, major structures undercut position; (b) Location of September 2009 undercut, drawbells and mapped damage to drives of the extraction level

The undercut advance during August 2009 and September 2009 period, was crossing a complex lithological domain where increased rock mass strain and bulking was observed to be occurring in the undercut drives. The undercut front was transitioning from the volcanic to monzonite domains, which included a tightly healed and continuous fault called Red Fault. A large complex seismic event occurred on the boundary of the volcanic and monzonite contact, where a fault splay was later identified (during post seismic event damage mapping) to have ruptured over 200 mm.

Routine damage mapping and convergence data at RWD was collected, commencing in 2009 (internal memo Capes 2009), for the purposes of understanding the rock mass response and capacity of the ground support systems and to ensure informed decisions could be made about the sequencing of the undercut. Data points were taken at locations in different lithological domains and in positions near the undercut front. The data was used to create a failure criterion and calibrate a Map3D model (internal memo after Cuello 2009). Information on drive deformation characteristics on the extraction and undercut level were collected through the visual monitoring of blastholes, convergence measurements, resistance wire extensometer) measurements, and other noted observations during production level inspections. A damage scale shown in Figure 23 was developed to use the blastholes to indicate different levels of stability in proximity to the undercut brow, which can be used to define the stress abutment and hence location of likely seismic activity.

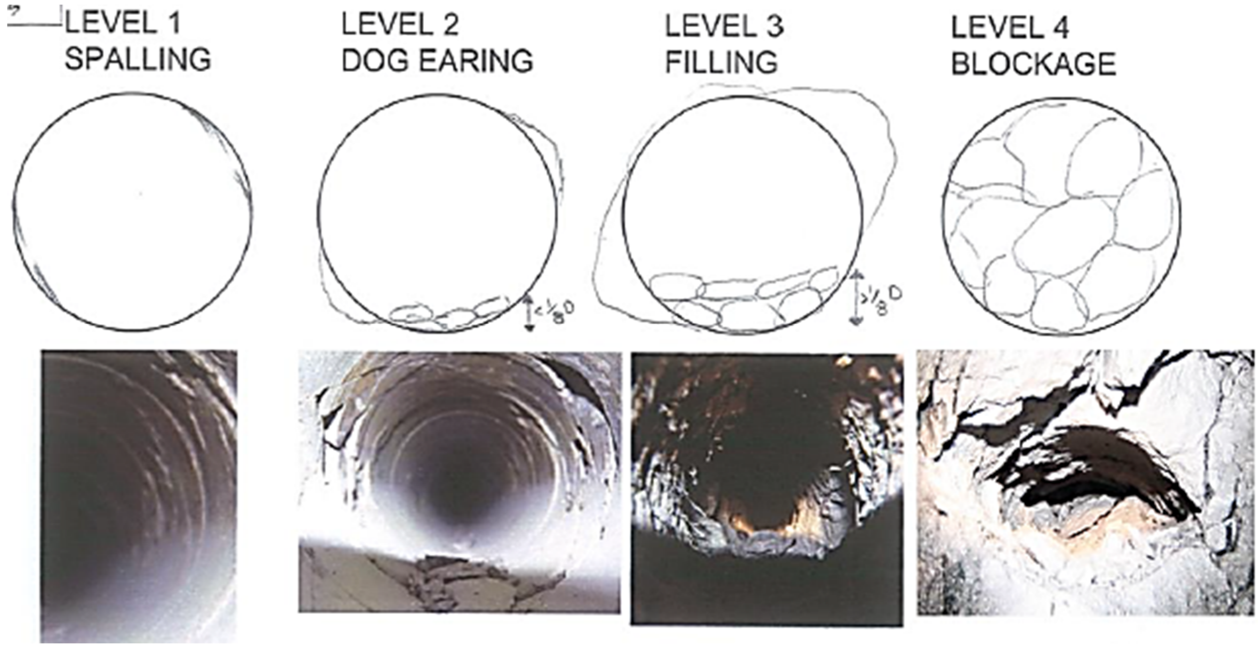
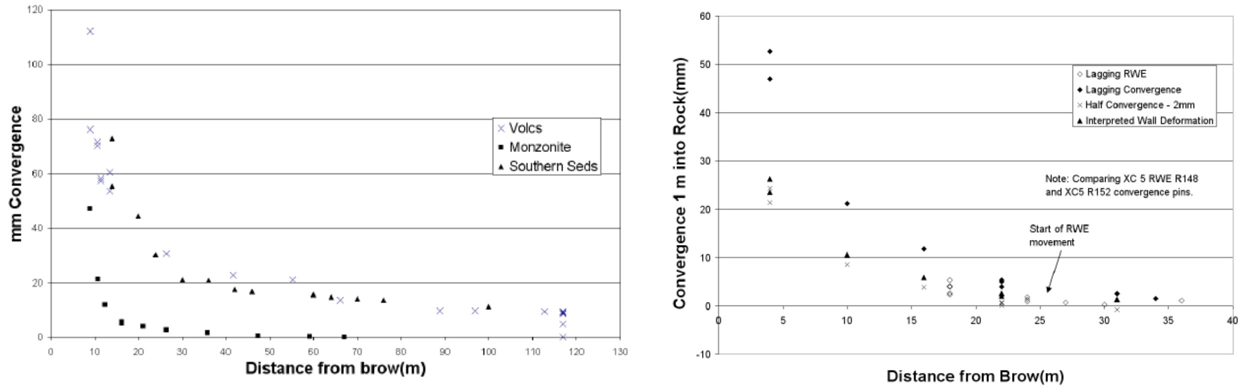


Figure 23 Damage criteria for Ridgeway Deeps production blastholes used to observe level of rock mass damage criteria, after Capes (2009)

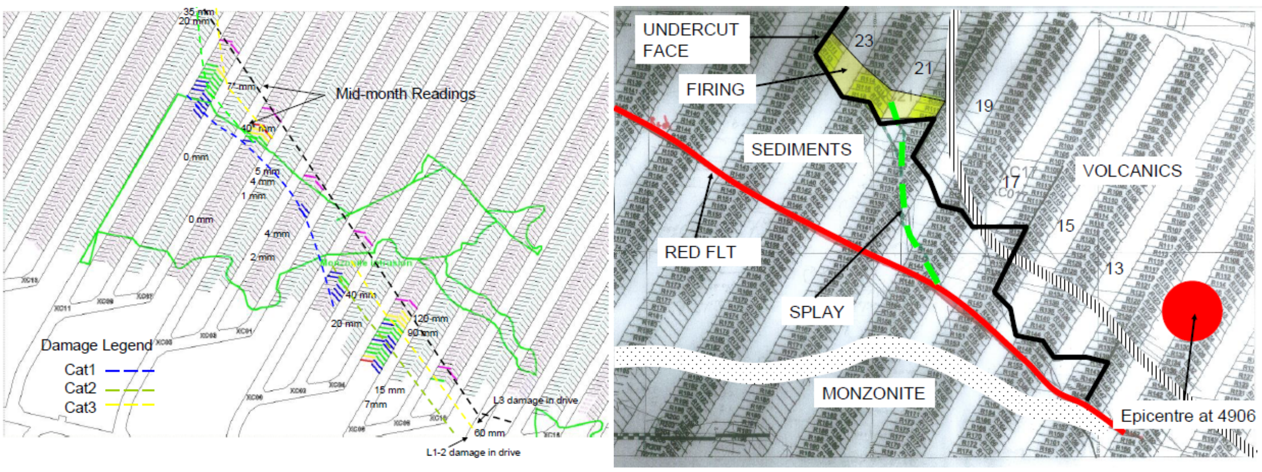
Damage mapping was undertaken monthly to examine changes in blasthole condition. The levels of blasthole stability are correlated to drive convergence. Convergence data from horizontal pins was collected on a daily, weekly, and monthly basis and input into a database that was used to monitor convergence. Examples of typical horizontal convergence data in volcanics, southern sediments, and monzonite is shown in Figure 24. Much of the convergence occurred within 10 m of the undercut brow and the volcanics and monzonite have significantly different convergence characteristics. The volcanics typically showed approximately 120 mm horizontal convergence within 5 m of the brow. The monzonite recorded up to 75 mm within 5m of the brow. The convergence data also demonstrates how long the overall distance from the undercut brow convergence was being distributed, up to 65 m in monzonite and 115 m in volcanics domains; this is due to the impact of the undercut veranda. Convergence data available in the southern sediments shows slightly higher values than the volcanics with respect to measurement carried out at similar distances from the brow.



(a) (b)

Figure 24 (a) Horizontal convergence of lithological domains on undercut. (b) Comparison of extensometer (1 m into wall) and convergence data in lagging undercut in the monzonite

At the end of each month, the blasthole damage mapping data was collated along with the convergence data on a plan, as shown in Figure 25a (July 2009 observations and convergence). This collated data was used with elastic modelling to develop a drive stability criterion. It has been generally observed that there is more damage to the ground support in lagging crosscuts compared to leading crosscuts caused by the stress path formed from the veranda. It was observed that rock mass strain in the form of overbreak and convergence was being accumulated between the undercut front and the Red Fault and monzonite contact, retrospectively, this increase in convergence was an indicator for the cause of the large damaging seismic event (as explained in the ISSI report).



(a) (b)

Figure 25 (a) July 2009 undercut level observations and convergence; (b) Location of large damaging event and the undercut blast and structural geology

Figure 26 illustrates the location of the local magnitude 2.5 event in proximity to the undercut and the overlying SLC, where the seismological analysis showed the event had a complex character and the source process indicated that yielding of undercut pillars had taken place and fault slip and displacement had occurred along the Red Fault. The overall synopsis of the event mechanisms was related to increased stress and strain that had been accumulating in the undercut pillars, exacerbated by the large undercut veranda that overall, created a large active volume above the undercut.

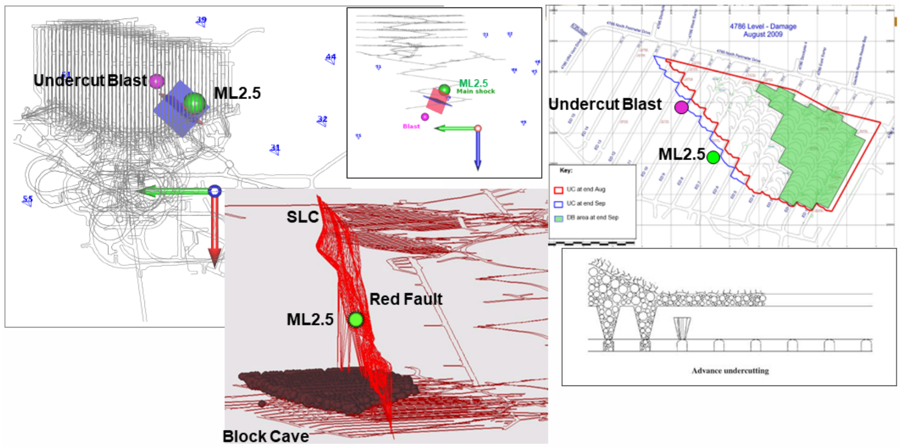


Figure 26 Ridgeway Deeps large seismic event location, position on Red Fault and undercut and drawbell geometry indicating length of undercut veranda

The synopsis of the September 2009 seismic event by ISSI International was summarised by Malovichko & Rebuli (2009) and issued as an internal report by Birch (2009).

The analysis for the large event used a full waveform moment tensor inversion technique to analyse the mechanism of the event. Refer to Figure 27 for schematics of the event location and mechanism. The source parameters of the large event were estimated using amplitudes of the intensive S-waves. The mechanism of the event was investigated using full waveform moment tensor inversion technique. The recorded low frequency waves of 13 triaxial sites could be reasonably well reproduced by a point source located ~70 m above the undercut blast. The point source includes an isotropic implosive component and a double-couple component. Isotropic component may be related to a coseismic compressive deformation (for instance due to collapsing of excavations). The double-couple component assumes reverse faulting mechanism driven by a near horizontal compressive stress. The nodal planes correlated with geological features existing within the source area.

The event had a complex character of a source process and that the rupture consisted of multiple phases. Using moment tensor techniques, ISSI identified two components of deformation that consisted of collapsing of pillars and slip on a structure in the orientation of Red Fault. The analysis was unable to decipher which mechanism occurred first, however, placed the major event with a source radius size of 80 m to have a centre point between 4,865 and 4,900 mRL near the Red Fault in the pillar between the block cave and SLC. The analysis found the main mechanism triggering the event was both isotropic component and a coseismic compressive deformation, due to collapsing of excavation pillars in the undercut.

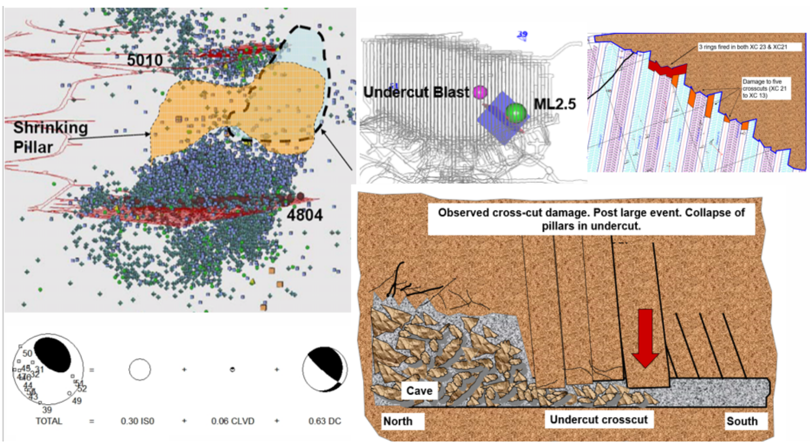


Figure 27 Section view illustrating seismicity between sublevel cave and block cave, location of the undercut blast and large seismic event, illustration showing full waveform moment tensor inversion technique to analyse the mechanism of the event

5 Comparative analysis of undercutting techniques

This section reviews the key parameters and metrics for comparison of the advanced and post undercut focusing on rockbursting and factors impacting production ramp up.

A large damaging seismic event occurred in PC2 in February 2015 on the abutment of the southeastern side of the undercut. The event occurred in the extraction pillars causing extensive damage that required a large campaign of ground support, ground consolidation and required the undercut to transition from post to advanced undercutting to complete the footprint. The transition from post to advance undercutting required the drill and blast design to account for the distance across the major apex, this was to ensure that the undercut was completely fired and to ensure that the risk of pillar collapse from incomplete breakage did not occur. The remaining undercut drives were drilled with the new advance undercut pattern prior to further cave stimulus, to remove risks of further rockbursting. The differences between the advanced and post undercut were assessed using risk assessments that focused on factors outlined in Table 6.

Table 6 Geotechnical factors used in assessing converting from post undercut to advanced undercut in PC2

Undercut time frame	Advanced undercut	Post undercut
Footprint development	Low to moderate stress on development	Low to moderate stress on development
Cave establishment	High-stress on undercut level Rock mass damage to undercut rings	High-stress on extraction level Rock mass damage to undercut rings and extraction level pillars
Production	High-stress and vertical loading on extraction level pillars Pillar collapse	High-stress abutment and vertical loading on extraction level pillars Pillar collapse

Previous performance at RWD block cave (advanced undercut), Cadia East PC1 and PC2 (hybrid post undercut and late conversion to advanced undercut) were benchmarked as part of the PC2 seismic recovery sequence, as plotted in Figure 28 to ensure that the PC2 project could be finalised and to ensure that the cave was propagated as per the full reserve. Note that the flat section of the PC2 plot in Figure 28 is the period of rehabilitation and re-establishment of the eastern portion of the footprint.

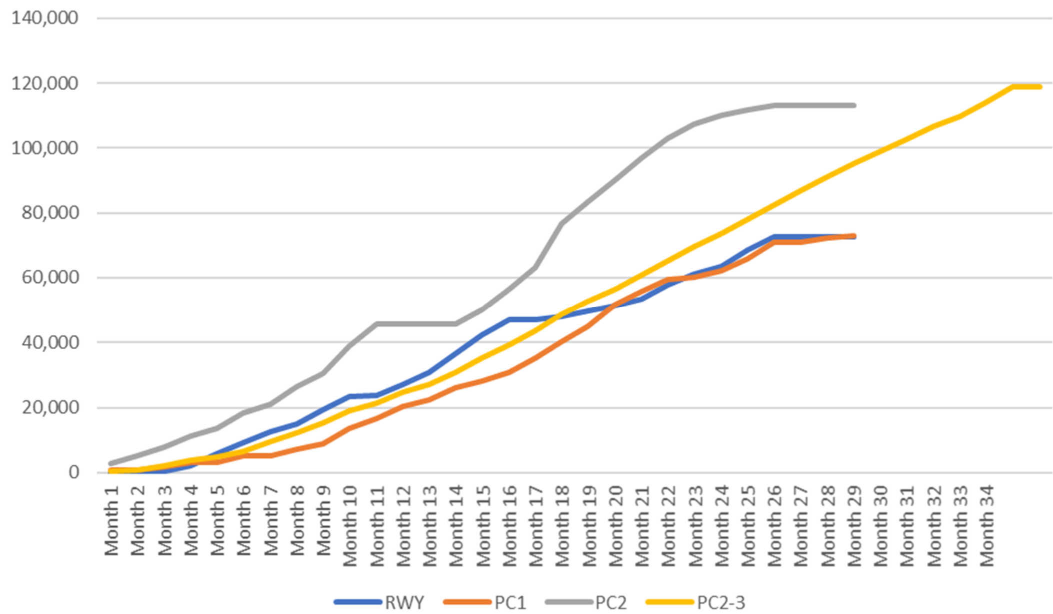


Figure 28 Cumulative undercutting in m² for Ridgeway Deeps block cave and Cadia East

During the investigation and rehabilitation of PC2 after the large event, the risk of producing frequent drawpoint hang-ups and coarse fragmentation was a concern. Commonly advanced undercut footprints have produced coarse fragmentation and higher frequency of drawpoint hang-ups. This has been due to the drill and blast techniques causing incomplete breakage over the major apex, which also can cause collapse of pillars over time. The risk of coarse oversize was assessed and further blastholes were drilled above the major apex to ensure breakage.

Fragmentation analysis has been undertaken routinely at Cadia East and the fragmentation results in PC2 show that previous concerns about coarse fragmentation produced by advanced undercutting were unfounded. Data collected at drawpoints in Cadia East showed trends of drawpoints becoming finer with draw maturity appearing consistent in the data. An area of particular interest is the eastern side of PC2, in which material is showing to have become finer in comparison to the western side (Figure 29). Table 7 shows a summary and comparison of the median d50 (50% passing particle size) fragmentation sizes for the eastern and western areas regions of PC2. PC2 east experienced a 30.9% decrease in d50 fragmentation size (0.064–0.046 m). Over a 3 year period the western side showed a 31.35% increase in coarse fragmentation size. This may be explained by the interaction of PC2 with PC1 and the caving which is currently occurring on the eastern side of PC1, potentially effecting the material in the western PC2 drawpoints.

Table 7 Comparison of 2021 and 2022 fragmentation (d50)

d50 particle size averages			
	2021 (m)	2022 (m)	% change
PC2	0.0621	0.0558	−10.22
PC2 East	0.0640	0.0456	−30.88
PC2 West	0.0596	0.0782	31.35

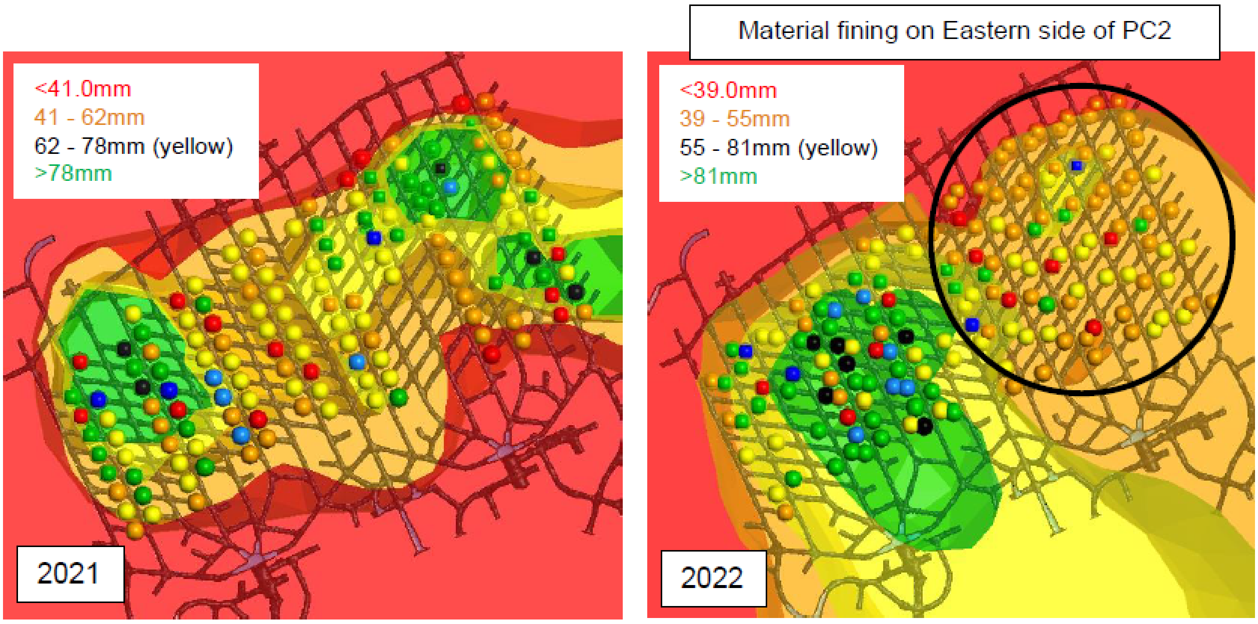


Figure 29 2021 versus 2022 interpolant fragmentation volumes (d50)

6 Comparative seismic analysis of undercutting

Information from seismic monitoring during the development of the adjacent caves, PC1 and PC2, and nearby RWD was analysed by IMS in 2019 to understand the seismic response from undercutting and to ascertain if there is a difference between an advanced and post undercut. Both seismic databases (Cadia East and RWD) underwent advanced processing for source mechanism analysis (Birch 2018a, 2018b).

It was understood that a possible correlation exists between the amount of deformation generated by the establishment of the footprint and undercutting, and the amount of cumulative seismic potency release observed during that time. Such a coupling would be useful in defining expectations for the rock mass response during development in future operations. The deformation generated by mine establishment can be represented by appropriate cumulative parameters directly proportional to the volume of deformation.

The following tasks were undertaken as part of the analysis:

- Separation of seismicity associated with footprint establishment and undercutting from seismicity associated with caving (selection of polygons based on predominant source mechanisms) for three cases (RWD, PC1 and PC2).
- Establishing a correlation of the cumulative seismic potency with area of the advancing undercut.
- Analysis of spatial-temporal correlation of seismicity with undercut firings for three cases, refer to Figure 30.

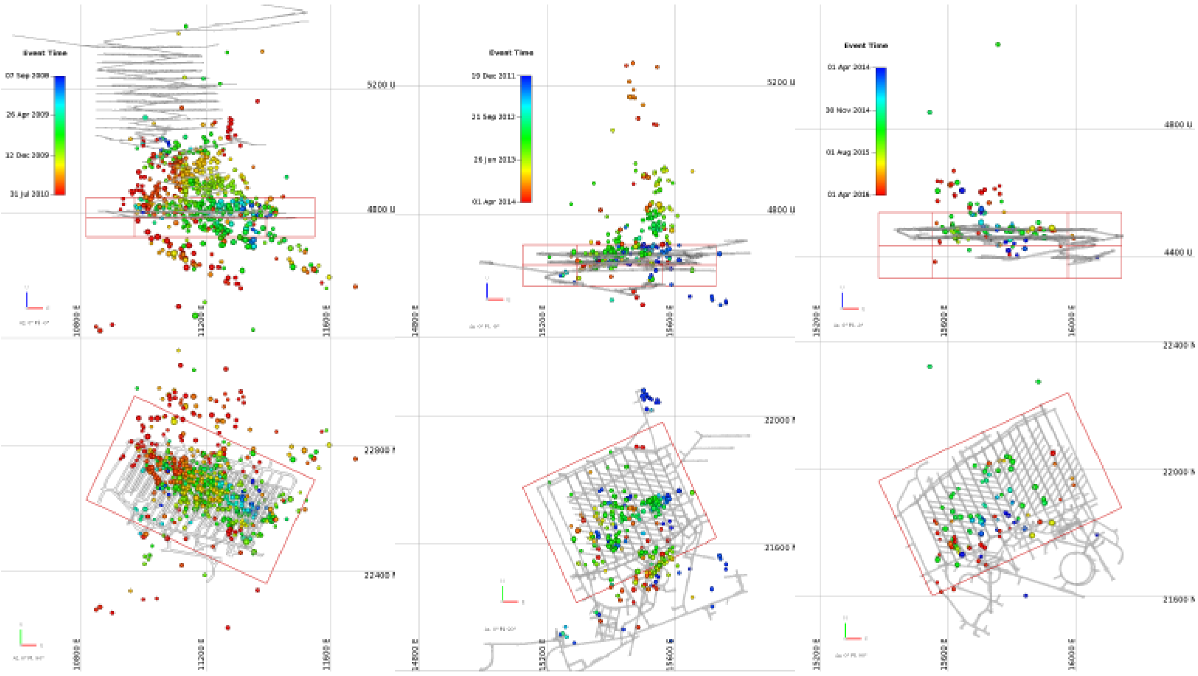


Figure 30 Events with magnitudes greater than ML0.0 included in the polygon at Ridgeway Deeps (left), PC1 (middle) and PC2 (right) looking north (top) and in plan view (bottom). Positions of the polygons around the undercut and extraction levels are marked in red

Spatial filters were applied to consider two scenarios for the seismogenic regions in each mine footprint.

1. Footprint establishment and undercutting, drives a mine-wide seismic response, i.e. caving-induced events are included.
2. Seismic response is confined to areas around the undercut and extraction levels only.

The cumulative undercut area was tested as a parameter which may control seismic response around the footprint of RWD, PC1 and PC2 caves. Data consisting of undercut firings were plotted and are presented in monthly steps (PC1 has bimonthly steps in the first half of 2012) plotted in Figure 31, to show the relative rates of undercut advance. PC2 experienced a damaging seismic event related to pillar failure on 25 February 2015 which paused undercutting for six months.

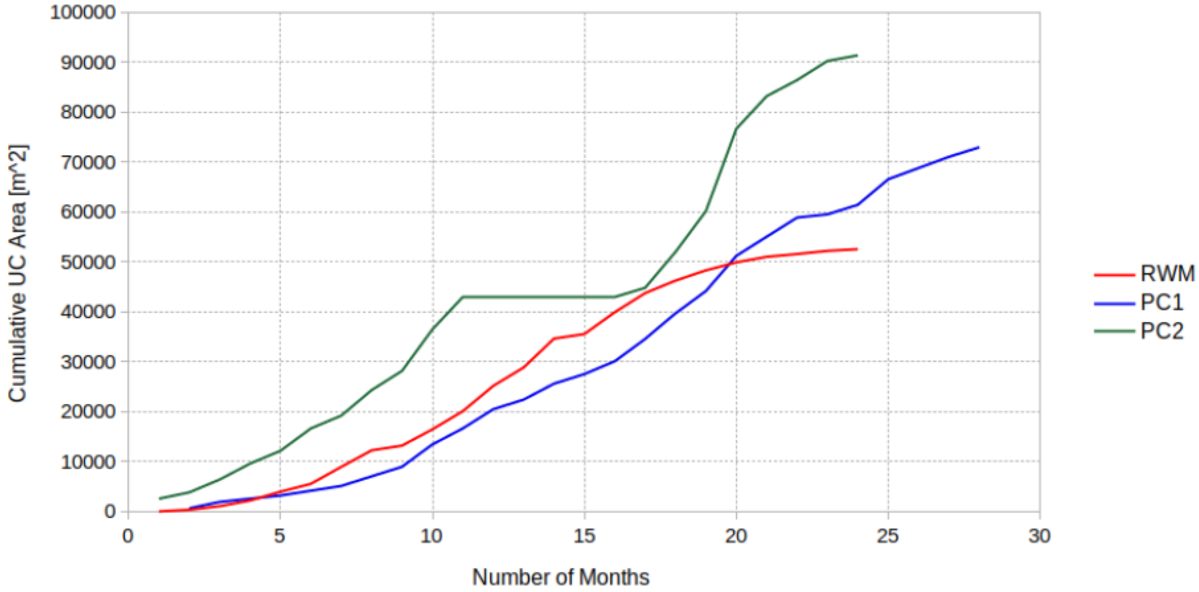


Figure 31 Undercut advance rates for Ridgeway Deeps (RWM), PC1 and PC2

The evolution of the cumulative seismic response in space (looking in plan section) is depicted in four 6-month steps in Figure 32 for events with ML > 1.5 recorded within the respective polygons. The events are coloured according to time and scaled according to local magnitude.

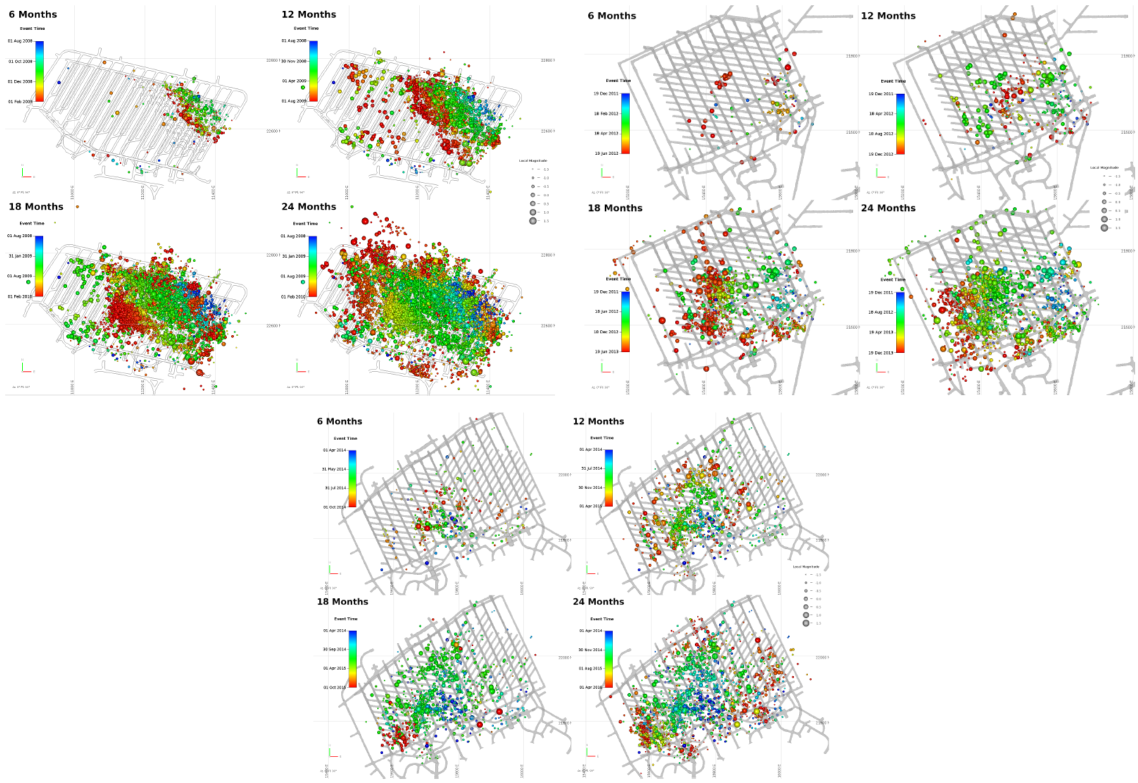


Figure 32 Evolution of Ridgeway Deeps, PC1 and PC2 cumulative seismic response in space (looking in plan view) during six-month steps in for events with ML > 1.5 recorded within the respective polygons

To consider cumulative undercut area as the parameter controlling the seismic response around the footprint of RWD, PC1, PC2 the ratio of cumulative seismic potency was analysed. Figure 33 shows the evolution of the ratio of cumulative seismic potency with the growth of the undercut area for three analysed cases (RWD, PC1 and PC2).

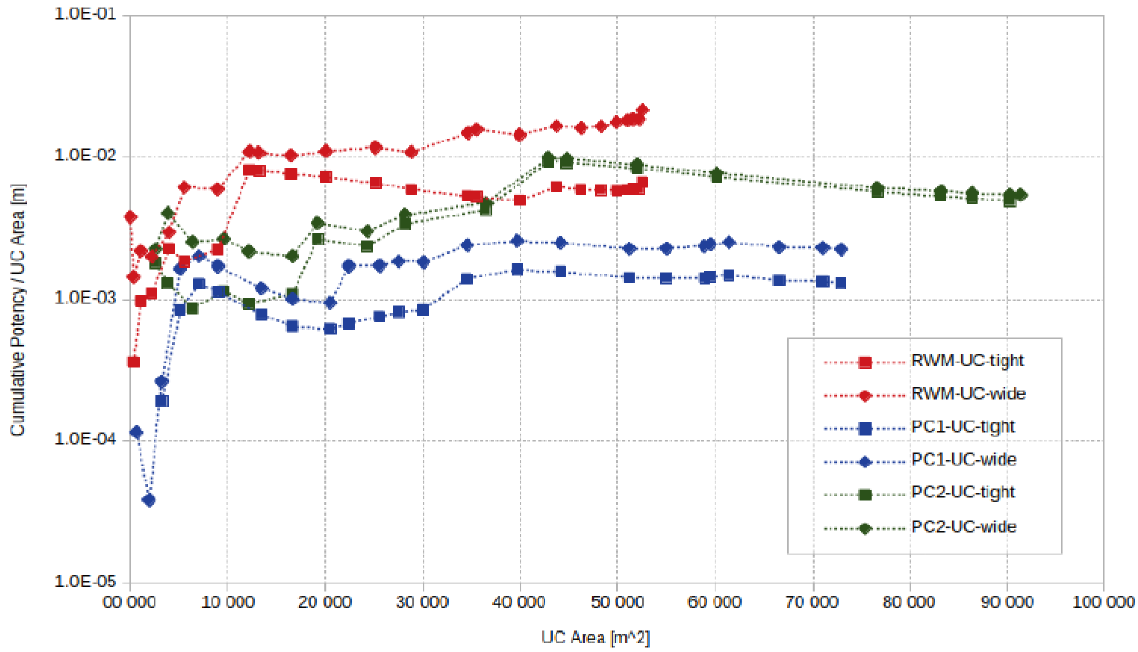


Figure 33 Ratio of cumulative potency to cumulative undercut area for Ridgeway Deeps (RWM), PC1 and PC2

The objective is to identify a ratio which can be considered as representative of future mining operations. The seismic response for a particular case (RWD, PC1 or PC2) may not be solely related to the expansion of the undercutting area. Other factors (e.g. local geology, spatial configuration of undercut front) may have a greater impact on the seismic response. Reviewing Figure 33, the RWD advanced undercut had the higher cumulative potency compared to the other post undercut datasets, owing to the undercut driving a large seismic active volume. PC1 had the lowest cumulative potency, which was accounted for in the smaller footprint size, well controlled undercutting rate and distribution of optimised sequencing using the hybrid post undercut (lower seismic response due to larger pillars). PC2 plotted the second highest potency due to the impact of higher stress and more brittle rock mass responses.

PC2 featured firing exclusion timeframes where barricades were put in place for 12–44 hours, in order to understand this the spatial-temporal analysis examines the correlation between rate of undercut firings with the spatial-temporal rate of seismicity for Ridgeway, Cadia East PC1 and PC2. Should a nonlinear increase of the seismic response be discovered, constraints on number of undercut firings per month per 1,000 m^2 may be a viable safety measure. The analysis of undercut area as a controlling parameter for seismicity suggests that seismicity recorded around the RWD, PC1 and PC2 footprints correlate with cumulative undercut area making this a suitable controlling parameter. A weaker seismic response was recorded in the case of PC1 and stronger responses were recorded in the cases of RWD and PC2. To make the results easier to interpret, the cumulative potency was translated to the number of events for different magnitudes.

Magnitudes of events are presented in terms of the Hanks-Kanamori (Hanks & Kanamori 1979) moment magnitude scale MW = (2/3) log P +0.92. The information presented in Table 8 is plotted in Figure 34. The level of seismic activity is higher at RWD for all events larger than MW1.0 per m^2 of UC advance, but for larger magnitudes (MW ≥ 1.5), the number of events with respect to undercut advance are similar. The correlation between the spatial-temporal rate of seismicity around the PC2 footprint with the spatial-temporal rate of undercut firings at PC2 was tested. There was no nonlinear (uncontrolled) increase in seismic response to undercutting.

Therefore, based on the analysis by IMS, the advanced undercut and post undercut method have similar levels of seismic hazard; however, the case of RWD shows that the advanced undercut had higher level of seismic activity due to the way the undercut was developed and in comparison, the PC1 undercut has lowest spatial-temporal and overall lower seismic response from the hybrid post undercut design.

Table 8 Assessment of expected seismic response to undercutting in Ridgeway Deeps and PC2

Undercut area (m^2)	Cum. Seismic potency (m^3)	Number of events* from respective potency frequency distributions					
		RWM tight: β = 0.83, logPmax = 2.67			PC2 tight: β = 0.681, logPmax = 2.78		
		MW>=1.0	>=1.5	>=2.0	MW>=1.0	>=1.5	>=2.0
		ML>=0.9	>=1.4	>=2.0	ML>=0.9	>=1.4	>=2.0
10,000	67	4.7	1.1	0.2	3.5	1.0	0.3
20,000	133	9.4	2.2	0.5	6.9	2.1	0.6
30,000	200	14.1	3.3	0.7	10.4	3.1	0.8
40,000	267	18.8	4.4	0.9	13.8	4.1	1.1
50,000	333	23.5	5.5	1.2	17.3	5.1	1.4
60,000	400	28.3	6.6	1.4	20.7	6.2	1.7

*Note that the expected number of events is presented, therefore, it is not an integer.

*ML was derived assuming an average energy for any given potency defined by log E = 1.4 log P + 4.8.

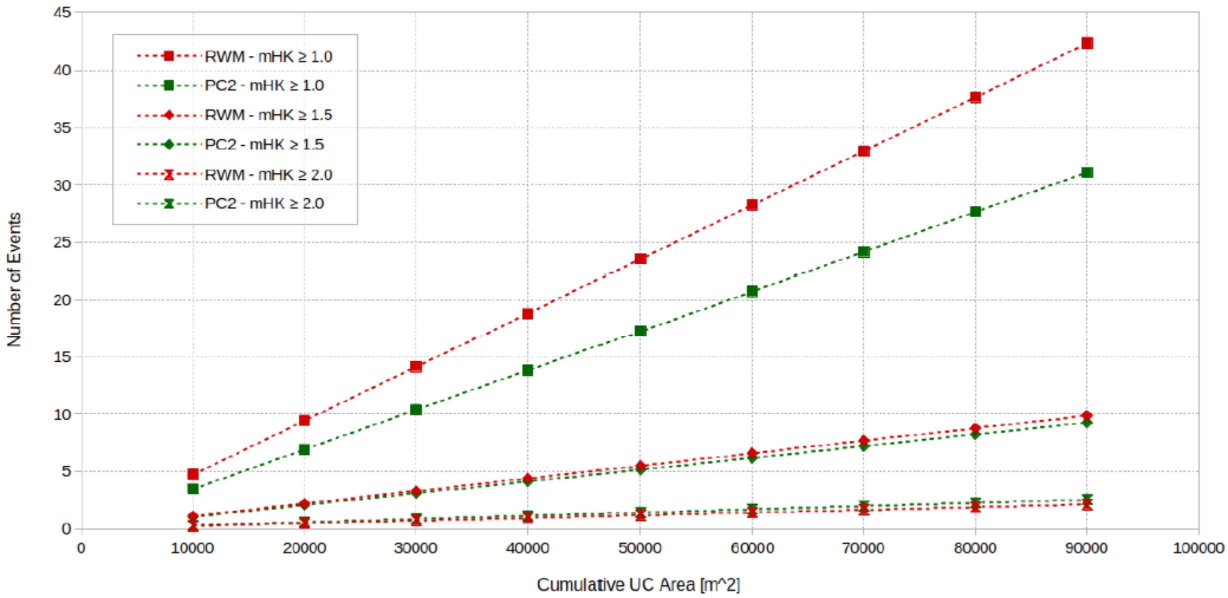


Figure 34 Expected response to undercutting at PC2-3 based on observations in the polygons for Ridgeway Deeps and PC2 (mHK=MW)

7 Discussion

The methodology of undercutting selection is often dependent on geotechnical properties, engineering properties and the requirements to manage the stress anticipated during cave establishment. Additional controls such as stress abutment exposure controls, seismic event exclusions, blast exclusions, and ground support requirement are part of the selection criteria. A key drawback of the post undercut method is the higher stresses present in the extraction level during undercutting and the exposure of workers within the stress abutment. The benefit of the post undercut is that production from drawbells can commence once the undercut is fired and return on investment can commence almost immediately. A key advantage of the advanced undercut method is that the drawpoint and drawbell development are constructed within the stress shadow. Hazards associated with the stress abutment from the undercut is removed as extraction and drawbell drives and other long-term excavations will not be subjected to damage from the undercutting front and require less ground support quantities. In comparison, a key weakness of the advanced undercut method is the higher amount of stress distributed on the undercut level during undercutting.

Structural geological impacts such as location of intrusive contacts, core disking and faults should be evaluated with diamond drilling as soon as practical to evaluate the risk of strainbursting (ranging to rockbursting) during all the phases of cave mining; especially the highest risk period during undercutting and cave growth.

The formation of the stress abutment is common in both undercut variants, the size, distribution and locations depend on the mine geometry. Stress magnitude, stress orientation, geological setting and ground support capacity are managed by geotechnical design. Overall, the post undercut has higher stress magnitudes applied to the extraction level compared to the advanced undercut, whereas the hybrid post undercut manages stresses and provides larger pillars to compensate for ongoing pillar damage and future rockbursting event.

Using empirical site data and numerical modelling the design of a hybrid post undercut provides a balance of benefits from both the advanced and post undercut.

8 Conclusion

Both advanced and post undercutting methods when established at depths deeper than 1,000 m have similar risk of creating large damaging seismic events and deformation during cave establishment, which impacts on the mining schedule and ramp up to production; this is evident from reviewing RWD and Cadia East cave establishment history.

The method of undercutting selection is often dependent on geotechnical properties, engineering properties and the requirements to manage the stress anticipated during cave establishment. As discussed in this research the pillar dimension and sequencing can determine the overall undercutting rate and advance, if attention is paid to reducing the overall mined volume to make the major apex pillars as large as possible. The comparison of the overall size of the RWD and Cadia East major apex pillars demonstrates a two-fold increase in pillar dimension which provides greater stability in deeper and higher stress conditions. The hybrid post undercut furthermore improves the stability of the undercut level by limiting the interaction of drives, drawbell and undercut voids; as shown in both the numerical modelling and site observations.

Additional controls such as stress abutment exposure, barricades, seismic exclusions, and ground support requirement also are part of the selection criteria.

A comparative analysis of advanced and post undercutting found that given robust assessment of the geotechnical conditions and stringent discipline to the mining sequence:

- Stress distribution will occur, and seismic hazard prevails in extraction level pillars and the undercut horizon.
- Dynamic ground support and seismic exclusions during production firings are required.
- Stress abutment exclusions for personnel will reduce exposure, however, abutments exist on both undercut level and extraction level regardless of undercut method.
- Spatial-temporal analysis of seismicity is lowest for an advanced undercut and hybrid post undercut compared to a higher response in a post undercut.
- Managing the seismic active volume will reduce likelihood of large damaging events in both advanced and post undercut designs.
- Novel changes to undercutting firings by using a lead and lagging sequence can reduce the overall mined void ratio, reducing rock mass deformation.

- Sequencing a hybrid post undercut brings all the benefits of production ramp up from a post undercut, with the control of an advanced undercut to reduce the overall excavated volume to improve the stability of the major apex pillars while lowering seismic responses.

The information discussed in this paper aims to demonstrate that both advanced and post undercutting methods have equal benefits and challenges, and an alternative undercut design is the hybrid post undercut. When factors impacting stability or schedule are encountered, issues that impact safe production can occur and must be risk assessed across all the major hazards. Limiting seismic hazard and rock mass deformation will provide the highest level of control to mitigate unplanned stoppages and re-work during the undercutting stage. Maintaining overall extraction pillar stability for steady state production should be the long-term priority for caving operations.

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