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Case study: Carrapateena caveback propagation and recovery

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Abstract

The Carrapateena sublevel cave (SLC) experienced a significant challenge between late 2020 and 2022 when cave propagation stalled within the Woomera Shale. In November 2020, following ten months of steady growth, the caveback rapidly grew without incident through the competent Upper Whyalla Sandstone into the overlying shale, growing 152 m vertically within 24 hours. However, from December 2020, vertical growth ceased despite ongoing draw, resulting in a steadily increasing airgap above the muckpile. By mid-2021, the airgap height exceeded 110 m, necessitating intervention to prevent further escalation, and to preserve safety and mine production.

The cave stall was attributed to multiple factors including uneven height of draw creating a buttressed 'verandah', stress redistribution limiting failure in the shale and the nature of the shale, which was a weak, highly laminated rock mass.

A multifaceted recovery strategy was implemented. Production was reprioritised to target draw beneath the underbroken verandah. Ring extensions were targeted to increase the undercut hydraulic radius. Extensive conditioning of the ground from surface was conducted and drilling commenced for mass blasting. These actions successfully induced caving activity and resulted in further cave growth over the next two years. Breakthrough to surface occurred in December 2022 with a minor seismic response, no observed airblast and minimal impact to mine production, marking a major milestone for Carrapateena.

The successful recovery was enabled by an extensive cave monitoring system array, allowing responses to cave engineering to be analysed quickly, and then used to inform plans and risk level sensitivities. Lessons learned in managing a cave stall include the critical role of understanding the rock mass in a cave column, the importance of real-time monitoring and employing adaptive draw strategies. This case study provides valuable insights for cave operations encountering propagation issues in highly laminated sedimentary rock masses specifically.

Keywords: *caving, cave propagation, case study, sublevel caving, hydraulic fracturing, cave recovery*

1 Introduction

Carrapateena is a copper-gold underground sublevel cave (SLC) mine located over 400 km north of Adelaide in South Australia. The project is located on Pernatty Pastoral Station, the supporting infrastructure is within Oakden Hills Pastoral Station, and the Kokatha people are the traditional owners of the land. The orebody is situated below 500m of barren sediments. Undercutting began in 2019 and the cave initially propagated well. In late 2020 the cave rapidly propagated vertically into the highly laminated Woomera Shale (WOOM), where it remained with no movement for five months until cave remediation activities began (Ormerod et al. 2024).

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2 Geological setting

The cover sequence at Carrapateena is lithologically simple: 500 m of overburden with layers of sedimentary units of various strengths, as shown in Figure 1. There are two units of note in this case study: the WOOM and the Upper Whyalla Sandstone (UWHY).

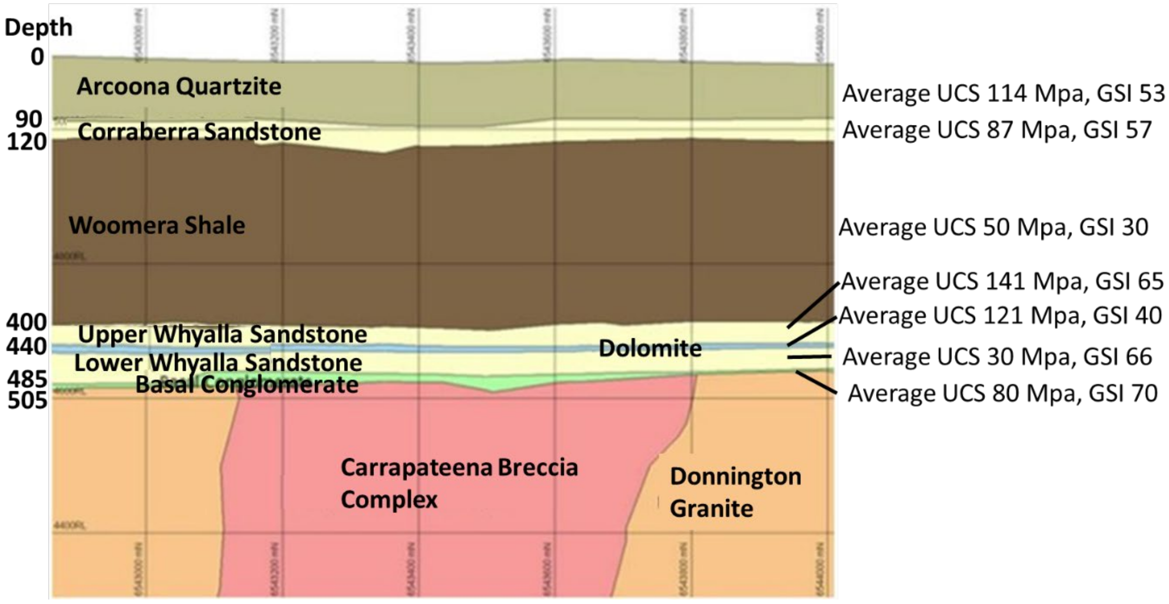


Figure 1 Carrapateena sublevel cave geological setting and average strengths: unconfined compressive strength (UCS); Geological Strength Index (GSI)

2.1 Woomera Shale

The shale unit is 240 m thick and the strength transitions in competence from a higher strength at the top to very weak and friable in the centre, then into higher strength at the base of the unit as it transitions into the UWHY unit. The base of the unit was assigned as the 'Woomera Transition Domain'.

To categorise the shale strength, a qualitative rock mass strength criterion was used which was analogous to rock quality designation but, instead of measuring defect intensity, the intensity of laminations was measured.

Due to the highly laminated, weak nature of the shale, stability and caving of this unit during mine development was a key concern. However, significant issues were not observed during development execution. The WOOM unit was not expected to be an issue with cave propagation (i.e. it was expected to cave easily) due to its anisotropy and low modelled persistence of structures.

2.2 Upper Whyalla Sandstone

Early models of the UWHY domain showed a strong (150 MPa), competent, massive sandstone with no identified major features. It was 90 m thick and so formed a strong beam in caving scenarios, which resulted in a potential cave stall scenario during feasibility studies. This prompted investigation for preconditioning methods.

Further assessment of the UWHY was conducted through observation of old cores, which showed that pervasive shale defects existed through the unit. This was revealed by shale disintegrating in cores from exposure to weather and diurnal effects. When the main decline reached the UWHY unit these shale defects were confirmed with face mapping. The strong 'beam' was limited to a 20 m core, with the top and bottom of the unit exhibiting far weaker geotechnical characteristics including regular vertical jointing. Following this more detailed domain definition, preconditioning of the unit was deemed not to be required. Despite this decision it was still expected that the UWHY would be the biggest issue for cave propagation and thus it was a significant milestone for the operation when the cave broke through this unit.

2.3 Cover sequence structure

There was only minor structure (aside from pervasive bedding) identified in the cover sequence, based on a significant effort to collect data during development. The majority of drilling was for orebody definition; the orebody was largely vertical and exploration holes were 'precollared' using reverse circulation drilling to the top of the orebody, from where diamond drilling daughters were then drilled. The spacing of diamond drilling useful for geotechnical characterisation would have been in excess of 100 m square.

3 Sublevel cave establishment

The SLC consisted of 25 m sublevels, with the first level at the 4,580 m RL, just beneath the unconformity approximately 500 m from surface. The first three levels of the SLC, the 4,580, 4,555 and 4,530, had set draw ratios of 40, 60 and 80% of in situ tonnes, respectively. This was to maintain an ore blanket for airblast risk management during cave initiation, which began in late 2019. Through 2020 the cave steadily progressed across the footprint and up into the lower sections of the cover sequence, which was monitored from surface with open holes, networked smart markers (NSMs) and cave tracker beacons, as well as a dense array of microseismic monitoring (Poulter et al. 2022).

Vertical growth rate slowed when the cave reached the competent UWHY, however, as lateral growth continued, the cave propagated steadily up into the unit, forming an estimated average airgap of 14 m (measured with open hole camera dipping from three holes).

On 27 November 2020 the cave broke through the competent UWHY into the much weaker WOOM. In the space of one shift the cave propagated 150 m vertically. This was primarily observed through microseismic monitoring, which showed an elevated activity rate in the lead up to the unit failing with an M_L+1.5 seismic event, followed by a flurry of seismic activity moving up through the shale. Growth was confirmed through open hole dipping with a wireline camera from surface. This event did not have any impact on underground operations, with only some reports of shakedown of dust from vent bags.

4 Cave stall and actions taken

Following the caveback propagation through the UWHY it was expected that the cave would propagate quickly through the shale due to its weak nature and expected 'good' caving conditions. However, by April 2021, monitoring showed no further growth of the caveback since the November event, and a steadily increasing airgap height measuring over 110 m at this time. Although the airblast trigger action response plan (TARP) was not triggered (calculated maximum air velocity from a hypothetical event was less than 10 m/s), it was at this point that initial actions were taken to attempt to stimulate caving, with the ultimate aim being propagation of the cave through to surface without significant further airgap growth.

As the cave was already established there were three main levers identified to promote cave growth: targeted draw, increasing the footprint size and attempting to reduce the rock mass quality around the cave through hydraulic fracturing or blasting. All three of these strategies were employed between May 2021 and November 2022 to get the cave to break through to surface, with various stages, learnings and results.

4.1 Targeted draw

Soon after cave stall, changes to the draw profile were identified as a lever to pull to encourage cave growth. It was recognised very early on that the draw profile to date was a large contributing factor in the current cave shape. There was very high draw in the east and centre of the footprint where the levels were initially established, and at the time there had been very limited draw on the northern and western extents of the footprint. Monitoring indicated that the cave was underbroken on the western flank (and on the north and south edges), where it had not broken through the strong UWHY yet.

A contributing factor to the draw height was that lower levels had higher draw percentages. At the time cave stall was declared, the second and third sublevels had commenced production, and the fourth sublevel was the first to have selective draw based on grade and not limited for airblast risk control.

The link to draw was also verified when plotting the total 'height of draw' at different points on the footprint which correlated extremely well with the measured cave height at these points, as seen in Figure 2.

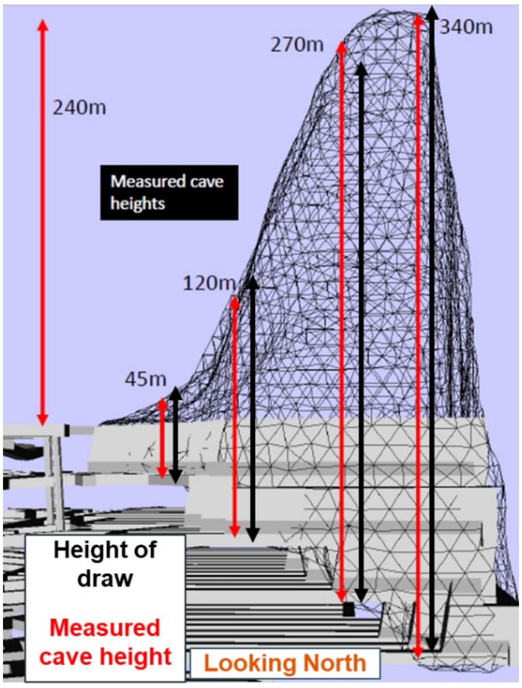


Figure 2 Correlation between draw profile and cave shape (view looking north)

To help encourage cave growth, additional draw was targeted beneath the underbroken areas of the cave, predominantly on the western side of the footprint. This strategy was also recommended by external caving experts.

Initial actions were to increase the speed of advance on the second level (4,555), such that more tonnes were bogged from the western zone, reducing draw in the centre column slightly by dropping the advance rates of the other levels. This was then combined with strategies to actually adjust the planned draw percentages and overdraw in targeted areas. The final rings (western edge) of the 4,580 level were overdrawn significantly, and all remaining rings in the 4,555 had the draw percentage increased up to 80% from 60% (of in situ ring tonnes).

Over the 12 months from June 2021 to June 2022, the planned draw on various rings was increased under the western cave verandah. Initial increase on the 4,555 to 80% was then adjusted to 100%, and then 125% in some areas. Two hundred per cent draw was completed on the western rings in the third sublevel (4,530) and draw was increased on the western rings in the 4,505 to a variable rate between 90 and 180% of in situ tonnes. Final executed draw ratios can be seen in Figure 3. All changes to draw ratio were carefully considered to balance the potential increased risk of mud rush, and management of change processes was employed.

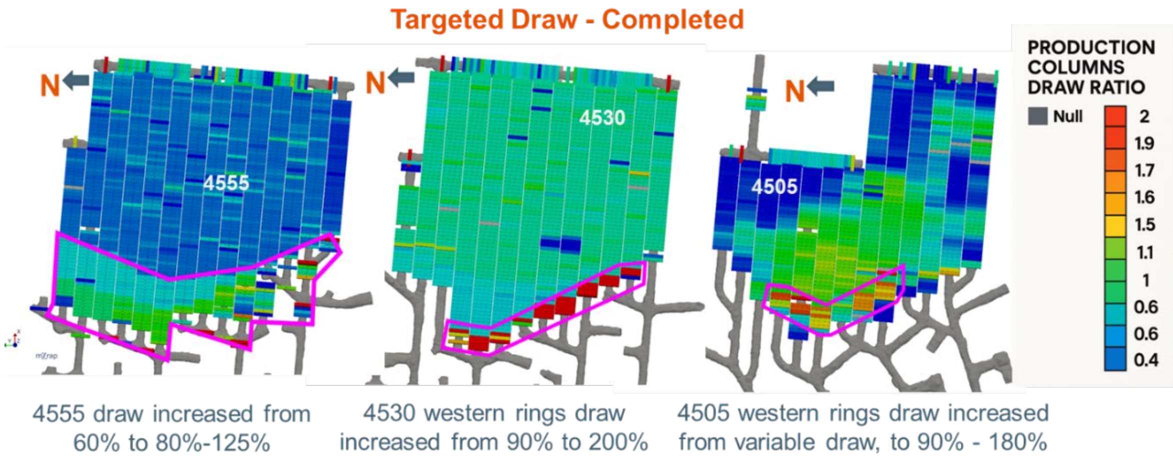


Figure 3 Completed draw on 4,555, 4,530, and 4,505 levels, showing changes to promote cave growth over the western verandah

4.2 Footprint expansion

In late May/early June 2021, after little change to the cave was observed, a large-scale footprint expansion program was planned. It aimed to expand the footprint on the 4,580 and 4,555, thereby increasing the cave undercut hydraulic radius. Footprint expansion was targeted at the southwest 'corner' of the levels where, due to the geometry of the footprint, the effect on the overall span of the undercut would be the greatest for the least cost. In total, 368 SLC rings were added across both the first and second levels.

To complete this, existing drives were utilised and a small number of new drives were developed. The expansion rings were designed with quite complicated geometry to utilise existing development as much as possible. Because of this, many rings were fired as mass blasts through intersections. The location and geometry of the extension rings is shown in Figure 4.

Targeted draw from the expansion rings was set to between 40 and 75% of in situ tonnes. This was optimised based on calculations for the minimum void required to enable caving up to the UWHY whilst also minimising draw of waste material, which came at a significant cost to the mine. Total achieved extraction was approximately 36% of the fired volume – just above assumed swell.

Figure 4 Ring extensions on the 4,580 and 4,555 levels to increase undercut hydraulic radius

4.3 Hydraulic fracturing

Preconditioning of the Carrapateena rock mass was considered in early study phases, however, it ultimately was not conducted prior to caving. This was because with a near-vertical minimum principal stress, induced fractures would have been approximately horizontal and at the same orientation as the existing weaknesses in the cover sequence (flat bedding). This would likely have resulted in minimal new fractures being created. Additionally, as early studies had highlighted the UWHY unit as the potential 'problem' for caving, this unit and not the WOOM would likely have been the focus of a preconditioning campaign.

After the cave was initiated, however, and was understood to have stalled in the WOOM, hydraulic fracturing for cave growth was reconsidered. It was hypothesised that the stress redistribution around the now existing cave would result in the minor principal stress being perpendicular to the caveback, which would help the fractures to propagate across the weak bedding of the cover sequence instead of along it. Hydraulic fracturing of the shale prior to caving would not have been as effective as ultimately the post-conditioning campaign was.

Two hydraulic fracturing methods were used to stimulate cave growth at Carrapateena: the 'straddle packer' method traditionally used in underground mining applications and the 'plug-and-perf' technique more commonly used in the oil and gas industry. Figure 5 shows the total completed hydraulic fracturing programs at Carrapateena in 2021 and 2022, which were all conducted from surface.

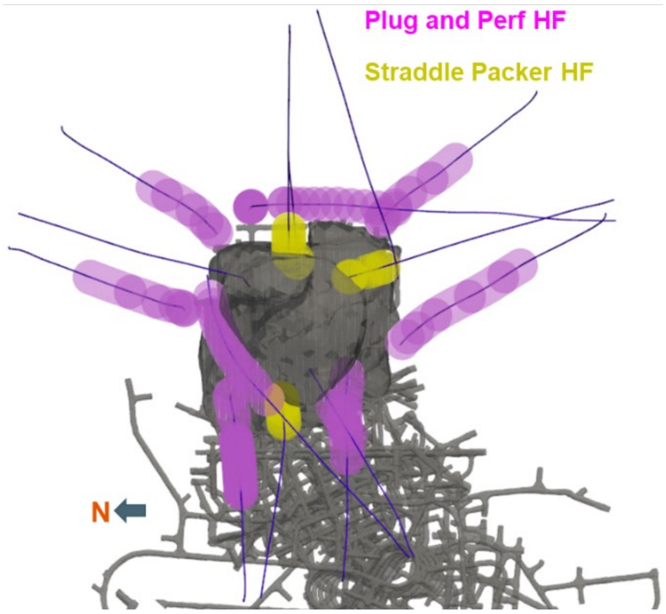


Figure 5 Completed hydraulic fracturing (HF) at Carrapateena (plan view). Note that the displayed fracture radius does not represent actual

5 Cave response

From when cave stall was declared in April 2021 and actions to recover began, the undercut expansion works and targeted draw only caused minor cave growth events. Finally, in September 2021, prior to any hydraulic fracturing taking place, a large growth event occurred over the space of several days. Growth was observed on the western edge of the cave, over the verandah that had been targeted with overdraw. This growth event was estimated (through cave monitoring) to be between 500,000 and 600,000 cubic metres.

Whilst the ring extensions and cave draw were not solely able to bring the cave to surface, they did play a critical role in increasing the width of the cave and contributing to the growth. Figure 6 shows a plot of the interpreted total cave volume above the production levels compared to the fired and bogged volume from 4,580 (the undercut level).

The similarity between the fired volume line (light blue) and the total cave volume (dark blue) can be clearly seen, especially in the highlighted red box when the 4,580 level was active, indicating that direct expansion of the footprint was a leading cause for cave growth in the early days prior to hydraulic fracturing.

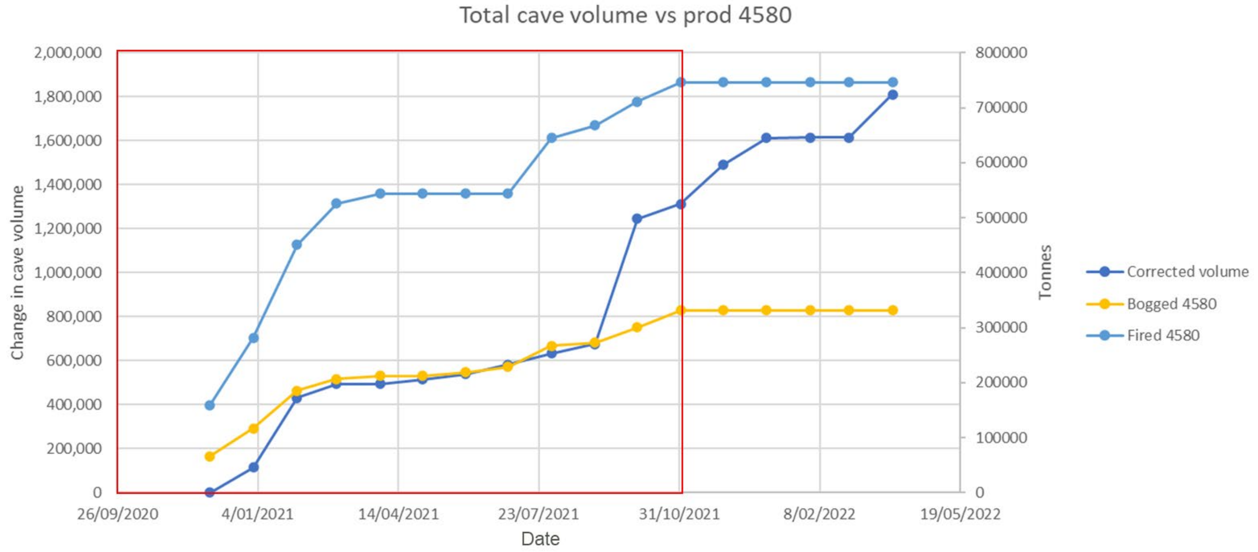


Figure 6 Cave growth compared to undercut level production rates. The red box shows when the level was active

In December 2021 the first hydraulic fracturing campaign commenced, initially using the plug-and-perf method. Cave growth response varied significantly between the individual programs, however, generally it was found that plug-and-perf resulted in significant and widespread damage, and often an instantaneous cave response. In contrast, the straddle packer method had a significantly milder response.

In December 2021, two holes on the western side of the cave were used for hydraulic fracturing in the first program. This program resulted in 15 to 30 m of vertical cave growth and significant seismic response around the caveback. At this point (end of 2021) the cave was 204 m from surface.

Overdraw continued on a stop-start basis determined by business needs and the ability to mine lower-grade material. Following the first hydraulic fracturing program, another significant growth period occurred between March and May of 2022. It was believed that this growth was influenced by a combination of targeted overdraw and hydraulic fracturing. The hydrofracturing that had taken place in late 2021 was above the western verandah and it was thought that the conditioning reduced the rock mass strength, and then the increased draw gave that rock mass room to fail. Cave growth over this three-month period was estimated to be around 900,000 cubic metres.

The next plug-and-perf program took place in June and July 2022. This program was completed in four holes around the entire cave and had significantly higher pump rates than the previous program. It resulted in 55 m of vertical cave growth and 39 m of lateral growth, or about 800,000 cubic metres.

By the end of this program the cave was about 90 m from surface and had finally progressed through the WOOM, reaching the Arcoona Quartzite and breaking through the Tent Hill Aquifer, which had been a highly anticipated milestone for the operation.

The next program took place in November and December 2022, completing hydraulic fracturing in additional holes and re-entering the upper sections of existing holes. The progress of operations in this period was incredibly slow as, by this point, the site had become aware of the potential risk of surface ejection reaching further than 250 m from the cave breakthrough, which is where the existing exclusion fence was (based on previous estimates of maximum ejection distance). A strictly controlled zone between 500 and 250 m from the cave was implemented, which was unfortunately where the existing hydrofracturing hole collars were located. In under a month the hydrofracturing contractors developed a system for remote conditioning which enabled the team to complete the job with no personnel access within the extended surface exclusion zone whilst hydrofracturing was occurring.

Despite the slow progress, this program proved to be a 'final straw' for the cave, which finally broke through to surface in late December 2022. The progression of the caveback over time can be seen in Figure 7.

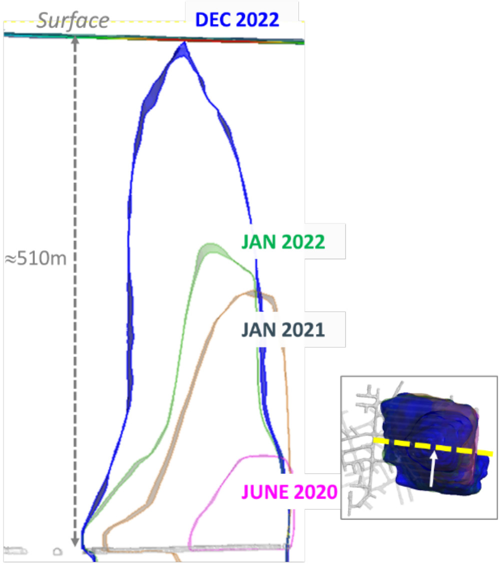


Figure 7 Cave shape progression from June 2020 to December 2022

Figure 8 shows the overall timeline of cave growth works conducted at Carrapateena from when the cave stalled in the WOOM. The works are overlaid on the cumulative seismicity around the cave, which was found to be a reasonable proxy for cave growth.

It is clear that the responses to different activities varied quite significantly. However, an important observation is that when no recovery works were occurring, the cave activity levels generally reverted to 'background' levels – indicating that ultimately it was the combination of all the recovery efforts that enabled the cave to eventually grow to surface, significantly de-risking the operation.

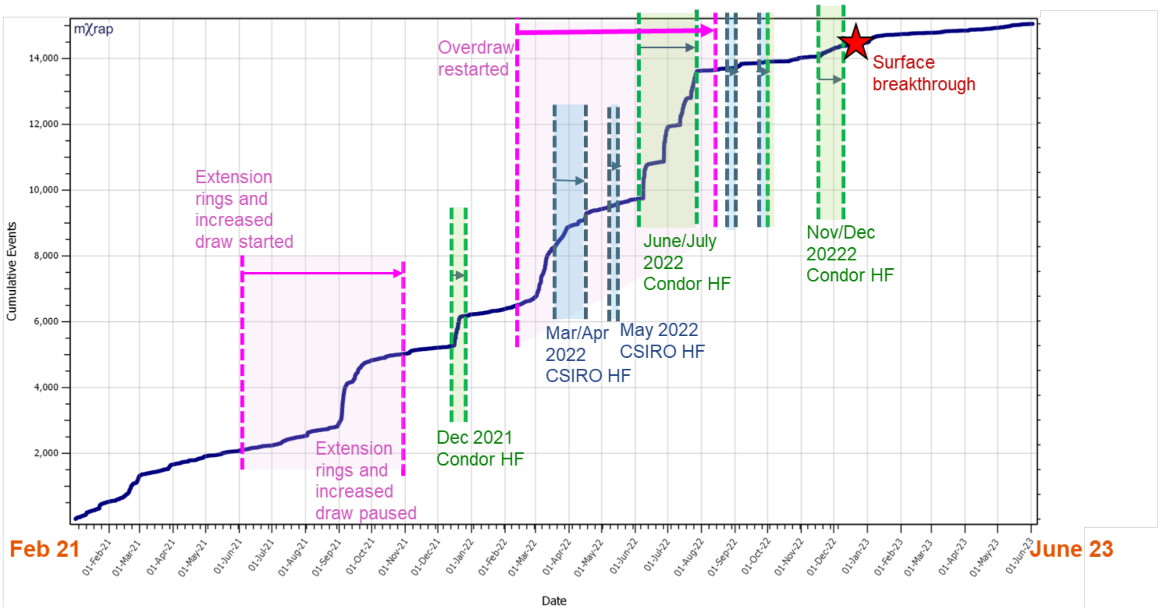


Figure 8 Overall timeline of cave recovery activities, overlaid with seismicity around the caveback a good proxy for cave growth. The plug-and-perf hydrofracturing timing is shown in green, and the straddle packer timing in blue

5.1 Hydraulic fracturing discussion

Prior to commencing the hydrofracturing campaign the team was unsure if the treatment would create new fractures or just leak off along the existing fracture network in the shale. Using an optical televiewer (OTV) the effect of the straddle packer program was able to be monitored by scanning a hole before and after treatment. The results showed that the damage caused by the hydraulic fracturing was extensive, both dilating existing fractures and creating new fractures (Figure 9). The OTV also enabled analysis of the fracture orientations. Where existing fractures had dilated, these were mostly horizontal, which lines up with the horizontal bedding of the cover sequence units. Where new fractures were formed, however, the orientation loosely aligned with the estimated orientation of the stress field (distribution around the existing cave void), which aligns with theoretical expectations.

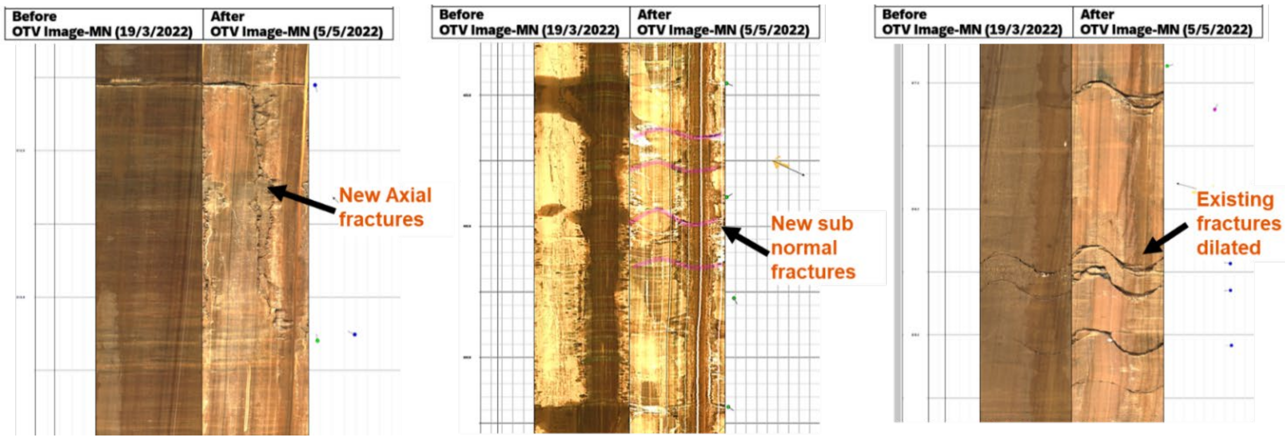


Figure 9 Comparative optical televiewer scans (OTV) downhole before and after straddle packer hydraulic fracturing, at three different depths downhole

Despite the clear effect of the straddle packer program on the rock mass, the programs did not immediately result in meaningful change to the cave or cave growth. However, the plug-and-perf method did prove to be incredibly effective at stimulating cave growth. It is hypothesised that this is due to the significantly larger injection rate from the plug-and-perf method compared to that from the straddle packer method: approximately 8,300 m^3 of water per minute for plug-and-perf versus only 0.8 m^3 per minute for straddle packer. It is likely that the higher injection rate was able to increase the pore pressure over a large area and hold fractures open, despite the leak off. This in turn allowed the rock mass to slip and deform rather than just creating new fractures.

A significant point of understanding was achieved during the June/July 2022 plug-and-perf hydrofracturing program through analysis of fibre-optic strain data in the crown pillar above the caveback. A significant increase in strain was observed from 10 June 2022, not just in the yielded zone around the caveback but through the entire remaining crown pillar. This correlated to an increase in seismic activity in the pillar and eventually an acceleration in the rate of subsidence observed from surface monitoring prisms (as seen in Figure 10). This demonstrated that the entire crown pillar was becoming compromised, and ultimately that the approach was working and it would only be a matter of time before further activities would bring the cave to surface.

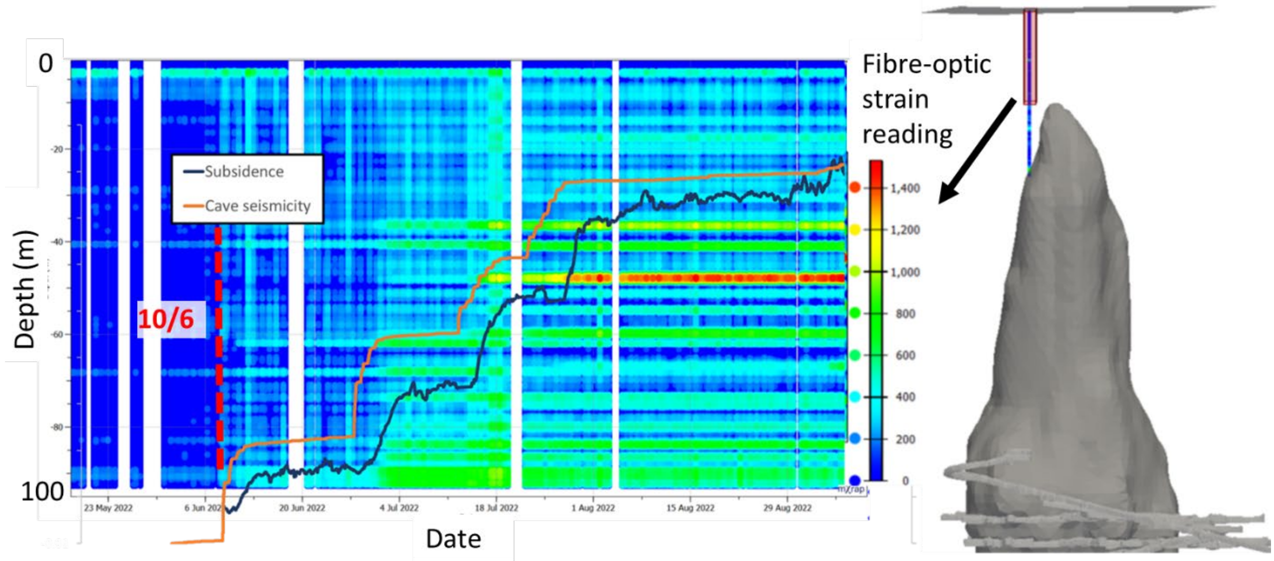
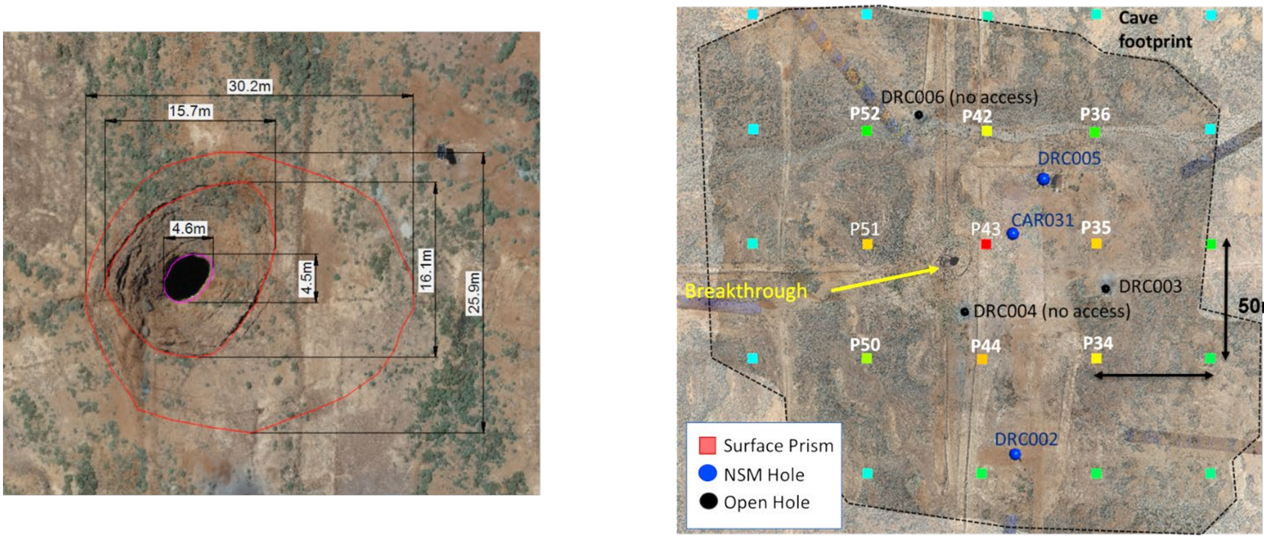


Figure 10 Plot of the fibre-optic strain in a section of hole in the crown pillar above the caveback, overlaid by cumulative seismic activity within the pillar, and total subsidence of the closest surface prism above. Note, no scale is shown for seismic activity or prism subsidence

6 Surface breakthrough

Surface breakthrough was observed on 29 December 2022 in a routine drone flyover. Retrospective analysis of surface prism movement and seismic activity indicated that breakthrough potentially occurred during the evening on 25 December, however, as the breakthrough could not be observed by the CCTV cameras monitoring the subsidence zone, this could not be verified. The reason that breakthrough was not immediately identified by any monitoring systems was due to the very small size of the crater, which had a diameter of only 4.5 m. Figure 11 shows the initial cave breakthrough measurements, as well as the location of the breakthrough relative to all monitoring points and the cave footprint.

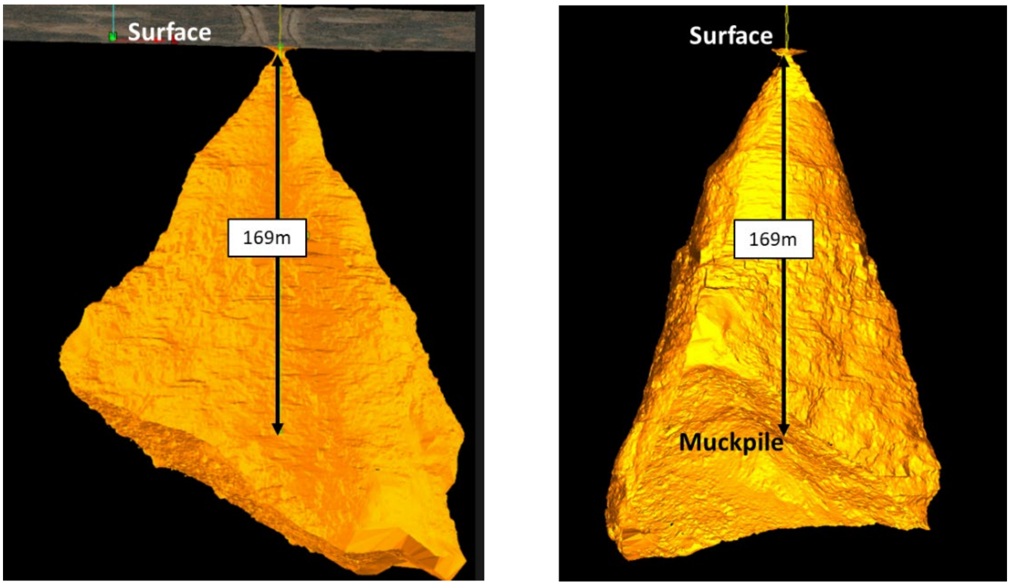


(a) (b)

Figure 11 Initial surface breakthrough: (a) Dimensions of the crater and surrounding cracking; (b) Crater size and position relative to the monitoring points and the underlying 4,580 undercut footprint

Despite the rigorous safety measures enforcing a hard 250 m exclusion zone around the crater, an additional restricted zone up to 500 m from the crater and contingency planning for a violent breakthrough scenario, there was no evidence of surface ejection or airblast. As far as all indications show, the event was gentle, controlled and unexciting.

After surface breakthrough, attempts commenced to achieve a 3D lidar scan of the cave void from surface using a remotely operated drone. In April 2023 a full scan of the open void was achieved and can be seen in Figure 12. The shape of the cave void was almost perfectly conical, which did not align with any of the initial conceptual or numerical models. Further interrogation of the shape indicates that it aligns with both real-world examples from overbreak in mines with similar conditions, and physical models replicating thinly interbedded units (Liu et al. 2021). It did not align with the commonly assumed and modelled rounded caveback shapes driven by stress fracturing in massive, brittle, isotropic material.



(a) (b)

Figure 12 Cave void lidar scan April 2023: (a) Looking north; (b) Looking east

Further scans in the time since cave breakthrough have shown a greater influence of major structures on the cave shape than was previously understood. Further work needs to be done to retroactively compare new scans with older cave interpretations from monitoring and analyse the cave behaviour through this adjusted lens. It does, however, reinforce the importance of good rock mass and structural understanding.

7 Learnings

The authors would like to share some learnings from the Carrapateena SLC propagation to aid future caving professionals when studying and executing caving mines. Below is by no means, however, an exhaustive list, nor a detailed back-analysis of the cave behaviour: merely a summary of the experience at Carrapateena.

7.1 Cave propagation

Firstly, as discussed in the previous section, the final cave shape upon breakthrough bore little resemblance to all cave shapes generated through numerical modelling and most conceptual expectations. The highly interbedded shale and cover sequence units performed very differently to what would be expected in more massive isotropic material, on which a significant amount of cave propagation learnings in the industry are based, including empirical caveability assessment tools.

For caving professionals it is important to continuously question assumptions and explore all possible scenarios. Use data to test and potentially disprove them, not just to reinforce existing beliefs. Evidence of the stable 'corbel arch' mechanism observed at Carrapateena can be seen regularly in the natural environment, such as in the arches formed on the Tasman Peninsula in southeast Tasmania.

7.2 Monitoring

The importance of a diverse and robust cave monitoring system is key. The value of information gained from an additional monitoring point is, almost always, worth significantly more than the cost to implement. Uncertainty in cave or airgap knowledge will drive operational decisions that ultimately cost significantly more than the cost of the drillhole or monitoring equipment. When designing a cave monitoring system, the full range of expected (and unexpected) cave scenarios should be considered – not just current models.

Further, the approach to monitoring must remain flexible and continually seek improvements. During the period between 2021 and 2023, significant changes and additions were made to the Carrapateena cave monitoring array. This was despite Carrapateena starting with, relative to most other operations, a very good monitoring system. As conditions changed (for example, losing access to surface monitoring directly above the cave), weaknesses and gaps in the system were revealed, as well as different applications for how the data would be used.

Finally, open holes remain the only means to a direct measurement of cave position and airgap size. This is critical for assessing airblast risk. There are many advancements in cave monitoring technology (for example, fibre-optic strain monitoring, muon tomography) that have already greatly improved, and will continue to greatly improve, cave knowledge and safe operations; however, it is important that the value of open holes is not ignored.

7.3 Post-conditioning

Ultimately, post-conditioning with hydraulic fracturing was the main driver that enabled cave propagation to surface after stalling in the WOOM and demonstrated that hydrofracturing in the shale still worked, despite some doubt that it would be effective. However, the response to individual fractures can vary greatly. When planning programs it is important to keep an open mind and be wary of anything that is stated or promised with absolute certainty.

Whilst a general understanding of the fracture plane and extent can be established through knowledge of intact rock properties and the in situ stress field, once begun, the direction and distance of fracture propagation cannot be controlled. Under the right conditions, the plug-and-perf fractures can travel several hundred metres, as was observed at Carrapateena – based on distance to observed fracture water ejection from an open hole on surface. Consider the necessary safety exclusions and production impact well ahead of time to allow exclusions and controls to be put in place.

The presence of ungrouted drill holes also must be considered. Connection between the fracture and ungrouted drill holes may result in ejection hazard in distant work areas, as well as reducing the fracture efficacy.

7.4 Draw rates and undercut size

It is obvious that undercut hydraulic radius is critical to cave propagation and thus to safe operations. The effect of early draw ratios is also well understood to be critical to cave propagation and risk management, and it plays a large role in dictating the shape of the cave. As shown in this paper, the planned draw ratios for the upper levels of the SLC had a significant impact on the ultimate shape and the resulting difficulties in managing cave growth through draw alone.

For blind sublevel caves aiming to propagate a long way, cave establishment should be treated with a similarly rigorous and iterative approach as is used during BC ramp-up periods (acknowledging, though, the great differences between the two production profiles and methods). This should involve continuous feedback loops between cave monitoring/interpretation and the mine plan (draw ratios and schedules). For an SLC especially, the production schedule plays a key role in exactly *where* draw will be occurring. Once the cavefront has moved past, opportunity is lost until the next level down, where it is less effective.

At Carrapateena, despite the main driver for ultimate cave breakthrough being the post-conditioning, it is believed that the efforts to increase the footprint size and increase draw beneath underbroken areas did still play a key role in cave recovery post-stall.

In general, there is very rarely one ‘ideal solution’ to a complex problem such as cave stall. At Carrapateena it was the combination of multiple efforts that ultimately led to breakthrough, with each being more effective at different phases of cave growth. For example, targeted draw and footprint expansions became less effective as the caveback moved further from the production levels. At this point hydraulic fracturing was more effective with shallower fractures propagating further and driving more cave growth.

7.5 Targeted draw strategy

Planning for all ‘phases’ of overdraw for cave growth at Carrapateena was highly reactive and the changes to draw ratio often ended up being planned at very late stages of the level’s progression. As overdraw on the rings would be low-grade or diluted material, any additional tonnes bogged for cave growth were at the expense of bogging other high-grade ore; thus they ended up being left until near the end of levels, waiting for positive information about cave growth and whether the overdraw would be required or not.

Major lessons learned from this period would be to plan required mitigation strategies as far ahead as possible, make stakeholders aware of what may be required if certain triggers are reached and have agreement on these strategies. A range of potential draw plans should be developed before operations begin and be used to respond to specific triggers comparing cave monitoring data to expected shapes at all stages (not just milestones). These potential measures should also be endorsed and accepted by upper management so that early action can be taken if necessary.

7.6 Operational management and communication of risk

A major challenge that was encountered during this period at Carrapateena was how to effectively communicate the risks of the cave stall to drive actions to remediate. Of course, the risk that is being managed is airblast (for Carrapateena, recovery was not a major factor as the cave was propagating through barren cover sequence).

Carrapateena had in place industry-standard TARPs for both cave stall and airblast risk. The cave stall TARP was based on knowledge at the time of writing, anticipating stall within the UWHY. The airblast TARP was based on potential wind velocities calculated from a theoretical collapse event. Airblast risk was well assessed and communicated by the geotechnical team, and later led to good collaboration with the ventilation engineers. Further details on airblast risk management can be found in Ormerod et al. (2024).

However, what the airblast TARP struggled to communicate was that, despite remaining in low trigger levels on the TARP, there was a significant potential likelihood of higher levels being triggered if no remediation actions were taken. In time it was found that this was a good method to communicate the risk to mine management and other areas of the business. For example, if no action was taken the operation would sit at a higher personnel risk level and significant production restrictions would be required to ensure that airgap size did not increase (as per the TARP). All actions should, and did, take place prior to triggering the actual airblast TARP.

Airblast is of course a very real risk with proven potential for devastating consequences. However, it is also a risk not commonly encountered in day-to-day operations for most mining personnel. Because of this, additional effort needs to be put in by geotechnical professionals to communicate the risk to all levels of the operation to ensure it is understood and that potential remediation measures are endorsed.

8 Conclusion

Carrapateena sublevel cave broke through to surface approximately 18 months later than expected due to stalling in the weak Woomera Shale. The cave stall in this unit was not anticipated or modelled in any prior work. A range of recovery efforts including targeted overdraw, footprint expansion and hydraulic fracturing were conducted at a large cost to the operation. Ultimately the cave successfully broke to surface with no incident, marking a major milestone for the site and for caving in South Australia.

Carrapateena demonstrated the unique uncertainties associated with caving and reinforces the importance to caving professionals of continuing to challenge assumptions and imagination. It also reinforces the value of collecting detailed geotechnical and geological information prior to operations, as well as making contingency plans for the unlikely or unexpected scenarios.

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References

Liu, J, Li, C, Shi, Y & Zhang, Y 2021, 'Stability analysis and fracture patterns of hard main roof in longwall top coal caving with large mining height', *Shock and Vibration*, vol. 2021, https://doi.org/10.1155/2021/9930221

Ormerod, T, Cox, D, Vejrazka, C & Poulter, M 2024, 'Case study Management of the risk of air blast at Carrapateena', in D Johansson & H Schunnesson (eds), *MassMin 2024: Proceedings of the International Conference & Exhibition on Mass Mining*, Luleå University of Technology, Luleå, pp. 373–384, https://doi.org/10.36487/ACG_repo/2435_C-06

Poulter, M, Ormerod, T, Balog, G & Cox, D 2022, 'Geotechnical monitoring of the Carrapateena cave', in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 487–500, https://doi.org/10.36487/ACG_repo/2205_33