

Geotechnical monitoring of the Carrapateena cave

M Poulter *OZ Minerals, Australia*

T Ormerod *OZ Minerals, Australia*

G Balog *OZ Minerals, Australia*

D Cox *OZ Minerals, Australia*

Abstract

Carrapateena is a copper-gold deposit hosted in a brecciated granite complex, located 460 km north of Adelaide, South Australia. The deposit is currently mined using the sublevel cave (SLC) mining method, with future mining to incorporate a block cave footprint beneath the SLC. The ore is located below 500 m of unmineralised rock cover.

Monitoring of the cave is a critical activity at Carrapateena, in order to understand the cave geometry, and effectively manage geotechnical risk related to cave propagation (air blast and subsidence). The SLC has no overlying monitoring level underground, and as such all monitoring is conducted remotely, or from surface. The cave monitoring system incorporates many different tools and techniques in order to reduce the uncertainty related to cave back interpretation. The critical analysis methods used in cave monitoring and interpretation at Carrapateena are: Networked Smart Markers (Elexon), Cave Tracker Beacons (Elexon), open hole camera surveys into the cave, active seismic tomography, a dense array of microseismic sensors around the cave back to monitor cave-related seismicity, and utilisation of volumes mined from the cave, to facilitate mass balance analyses.

There have been many learnings throughout the time the Carrapateena cave has been monitored. Firstly, the certainty provided by physically inspecting both the cave back and muckpile through a camera in an open hole, is currently, and in the opinion of the authors, the most valuable monitoring tool for cave back and airgap interpretation out of all the tools in place at Carrapateena. Contingency in the form of multiple holes should be accounted for in design.

Secondly, defined limits and forward planning is required for when surface restrictions will be necessary due to potential subsidence, to allow time to convert any monitoring systems to remote setups. Ideally, this functionality could be incorporated from the beginning.

Lastly, thorough analysis should be undertaken prior to installing monitoring systems to understand the most likely cave shape and potential propagation. Monitoring arrays should be treated holistically as a combined monitoring system, instead of individual systems, with an understanding of the risks associated with each, and the resulting uncertainty for various areas that will be monitored.

Keywords: *caving, cave monitoring*

1 Introduction

Carrapateena is a copper-gold underground mine located approximately 460 km north of Adelaide in South Australia's highly prospective Gawler Craton. The project is located on Pernatty Pastoral Station and its supporting infrastructure is located within Oakden Hills Pastoral Station. The Kokatha People are the traditional owners of the land.

The Carrapateena orebody is overlain by 500 m of sediment cover. First saleable concentrate was produced at Carrapateena in December 2019, with caving being initiated soon after. A significant monitoring array was installed prior to cave initiation and has been progressively updated as the cave has grown. During the cave

propagation period, monitoring of the cave is critical to aid understanding and assist with management of critical risks, air blast, and cave subsidence. Effective management requires a detailed understanding of the cave, airgap, and muckpile size, shape, and location.

Multiple methods have been installed and interrogated at Carrapateena to monitor the progression of the cave and the muck pile. No single monitoring source is suggested, instead a system of monitoring to build redundancy and supplement data is advised. While multiple systems were used and should continue to be, some have given better data and more robust interpretation than others.

Definitions of caving zones used are as per the Duplancic (2001) conceptual model, shown in Figure 1.

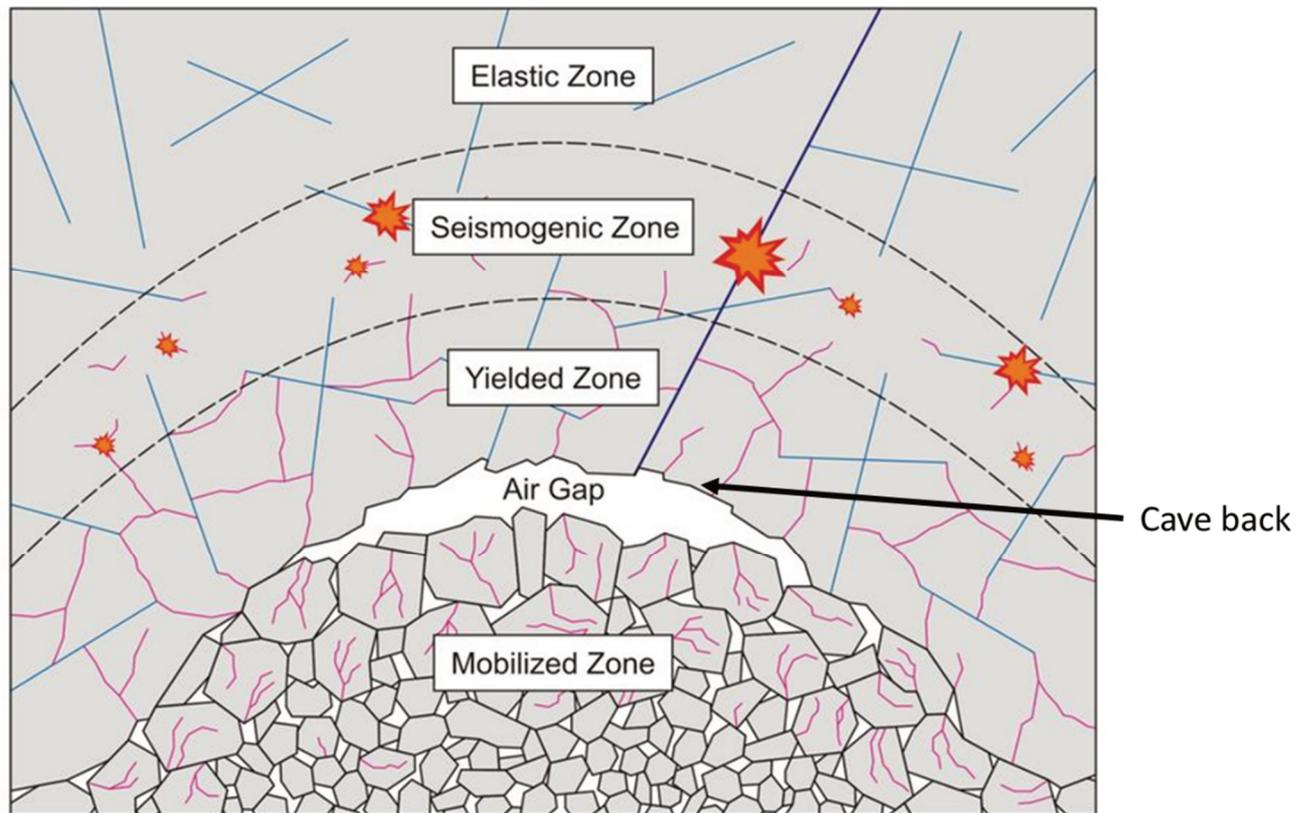


Figure 1 Conceptual model for caving and terms employed at Carrapateena (after Duplancic 2001)

2 Monitoring methods

An array of different types of monitoring methods are employed to monitor the Carrapateena cave back. The main methods used regularly for cave interpretation will be discussed. It should be noted several other systems are in place or in trial, however, are currently not used on a regular basis for cave monitoring.

Table 1 shows the cave monitoring methods and capabilities in use at Carrapateena and their capabilities.

Table 1 Cave monitoring methods and capabilities in use at Carrapateena

| Monitoring method | Cave back position | Top of mobilised zone ('muckpile height') | Muck flow |
|---------------------------------|------------------------------------|-------------------------------------------|-------------------|
| Open hole dipping (camera) | ✓ | ✓ | ✗ |
| Open hole dipping (weight only) | ✗ | ✓ | ✗ |
| Networked Smart Markers | ✓ | ✗ | ✓ (inferred only) |
| Cave Tracker Beacons | ✓ | ✗ (can be inferred at initial growth) | ✓ |
| Fibre-optic strain | ✓ | ✗ | ✗ |
| Microseismic monitoring | ✓ (inferred only) | ✗ | ✗ |
| Active tomography | ✓ (inferred in retrospect only) | ✗ | ✗ |
| Metso RFID tags | ✗ (can be inferred once recovered) | ✗ | ✓ (Inferred only) |

All monitoring methods have benefits and limitations, which will be discussed below, as well as learnings that have been gained over the time they have been in use at Carrapateena. The Metso RFID tags will not be discussed, as they are currently, purely a flow monitoring tool and have not been used to interpret the cave back position. Their use at Carrapateena is discussed in Hocking et al. 2018).

All comments regarding effectiveness and limitations are based on the experience of the Carrapateena team, and how the systems have been used by the site. The comments are not necessarily in regard to the full capacity or potential of the systems.

2.1 Open hole dipping

Open hole monitoring at Carrapateena consists of lowering a wireline camera or a weighted dipper down an open hole that connects directly into the cave. It is the only direct observation of the muckpile, and when using a camera, the cave back. Because of this, it is regarded at Carrapateena as one of the most valuable monitoring data points when creating interpretations of the cave shape and position. Figure 2 shows a view of the muckpile taken from the hole dipping wireline camera.

The hole dipping array at Carrapateena generally consists of around three open holes that intersect the cave in different locations. Initial holes were drilled vertically from the surface, both to reduce drilling length, and reduce the instances of dislocations or hole imperfections affecting the ability to lower the camera down the hole (it is harder to lower the camera down a hole with a shallower angle). Due to the holes passing through an aquifer prior to intersecting the cave, significant water flow over the camera can make it difficult to distinguish minor details. This is managed through lining of holes where possible, and the use of makeshift shrouds around the camera to lessen the water flowing over the lens. For regular hole dipping, this makes it possible to determine the cave back location, and the top of the muckpile, however, distinguishing details such as minor dislocations or hole damage is much harder and therefore this data is collected infrequently.

Occasionally, to obtain more information through a better visual of the cave back and muckpile, purpose-built camera and lighting arrays have been lowered, and provide a much clearer view to note specific details inside and in proximity to the cave void. This was completed using multiple commercially available rugged video cameras attached to a custom light source. An example is shown in Figure 3, which is a snapshot from one such survey showing the very flat cave back symptomatic of caving through a highly laminated shale unit. This type of camera survey is very labour-intensive and is therefore not conducted on a routine monitoring

basis, however, when it is completed the high-quality footage and vision of the cave back, muckpile, and borehole is extremely valuable.

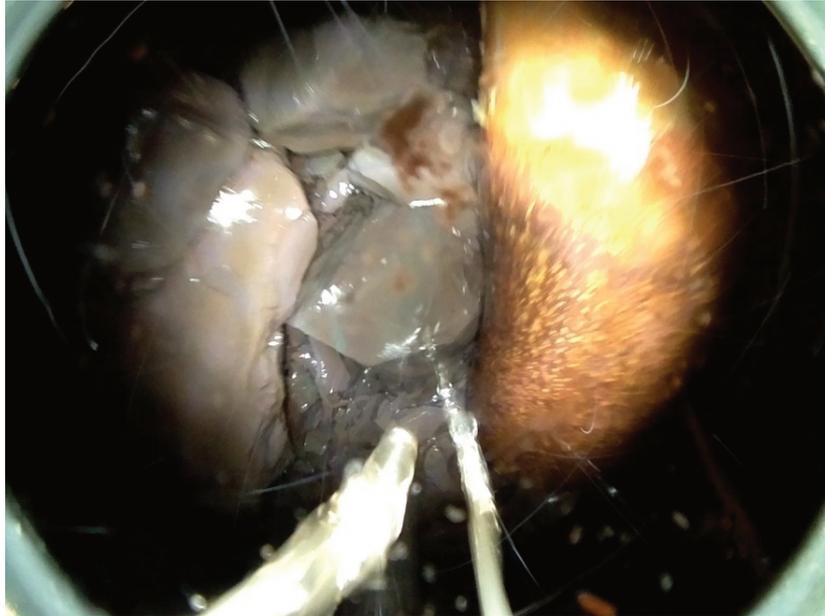


Figure 2 View of the top of the muckpile from the wireline hole dipping camera



Figure 3 Snapshot of the cave back showing the large, flat cave back and the wall of highly laminated shale beds

When access was not permitted directly above the cave void on surface due to subsidence risk, one hole was set up with a remote camera dipping system that could be operated from a safe distance. Another hole was set up with a similar remote dipping system, however it only consisted of a weighted dipper, not a wireline camera. This system was used in a hole on the 'flank' of the cave to lower and measure the depth of the top of the muckpile, however, it was not able to capture the location of the cave back. This dipper still proved effective in tracking muckpile height, and when the muckpile moved upwards, cave growth was inferred.

2.1.1 *Limitations*

Limitations of the open hole dipping method at Carrapateena are that it is a relatively labour-intensive method of collecting data as someone must be present for the entire duration of dipping a hole. Depending on the depth, this could translate to many hours spent per week dipping multiple holes, in order to gain a low quantity of data on the cave. However, this is generally offset by the value of the data points, giving the only direct observations of the cave back and muckpile out of the entire monitoring array on site.

Additionally, once access to the vertical holes directly above the cave is lost and holes must be angled (to ensure they are drilled from a safe distance away, but still target the cave back), the effort required is higher. Holes are more likely to become blocked with mud and salt build-up that runs along the base of the hole than in a vertical hole, and any dislocations are likely to hinder the ability to run a camera or weight down the hole much sooner. This is of course in addition to the increased drilling cost for longer holes.

2.1.2 *Learnings*

One of the predominant learnings from hole dipping at Carrapateena is the difficulty experienced through intersecting an aquifer with the open holes into the cave. Where holes are un-lined through the aquifer and water is able to run down the hole, it significantly impacts the visibility through the camera lens, and as mentioned above, increases the chances of blockages, particularly in angled holes. The additional time and cost to line a hole is generally worth the increased visibility and reduced maintenance requirements, and the higher confidence in the footage of the cave back.

At time of writing, the quality of the available and accessible wireline camera monitoring remains quite poor, relative to the cost of a system. Footage can be hard to interpret, and connection issues are common at the depths required. Additionally, the inbuilt lighting is often not sufficient to view larger areas (such as when the camera exits the drillhole into the cave). The benefit of the wireline cameras is the recording of the accurate depth from the wireline winch in tandem with the footage, which cannot be done on conventional, commercially available rugged cameras (e.g. GoPro). However, the quality of footage, and relative very low cost of these cameras, make it desirable to continue their use as a supplementary system. At Carrapateena, this is generally done by attaching the rugged camera to the wireline camera and reviewing the footage based on the timestamp to estimate the depth. Additionally, a separate light source is often also attached to this set up, for increased confidence in the cave back and muckpile observation.

It has also been critical to ensure multiple wireline cameras are available, for redundancy in the system. In the rugged environment they are subject to, it is common for the sensitive electronics in these systems to fail and require maintenance, and alternatives must be available to ensure cave monitoring frequency is not negatively affected. This is also applicable due to the risk of losing or damaging a camera during dipping, as the cave is a dynamic and constantly changing environment.

A further learning from the hole dipping was the value of planning for when access was lost to the collar of the monitoring holes. Allowing as much time as possible to build redundancy and remote operating and maintenance options into the monitoring system was crucial, particularly for the open hole dipping as the most valuable, direct observation of the cave and muckpile. This also includes consideration for the maintenance requirements, in particular cleaning of the camera lens. Where possible, robust systems would be set up to allow remote cleaning of the lens in order to preserve the valuable monitoring method, without having to put personnel at risk entering a restricted area. A system of pumps and water sprays was set up at the remote Carrapateena camera dipping system. It had some success, however due to the previously mentioned aquifers and subsequent salt build-up, it did not remain successful, and the quality of the footage degraded over time. Efforts should be made into planning for a cleaning system if setting up remote camera dipping.

2.2 Networked Smart Markers

Networked Smart Markers (NSM) from Elexon Mining are currently used at Carrapateena, predominantly for cave back monitoring. They can also be used for flow tracking, through interrogating recovered markers from the SLC drawpoints. The system consists of smart markers that are able to communicate via radio frequencies to other neighbouring markers within range, record the radio signal strength between markers, and transfer the data to a reader (Elexon Mining 2016). The radio signal strength can be related to the distance between markers, with changes indicating movement (e.g. dilation) between markers. Once markers are too far apart, communications are interrupted (Elexon Mining 2016). This most often occurs when markers fall into the mobilised zone from the cave back, indicating to geotechnical engineers that the cave back has grown at that point. Figure 4 shows an example of the array of NSMs around the cave back, which are all used to interpret the cave back position.

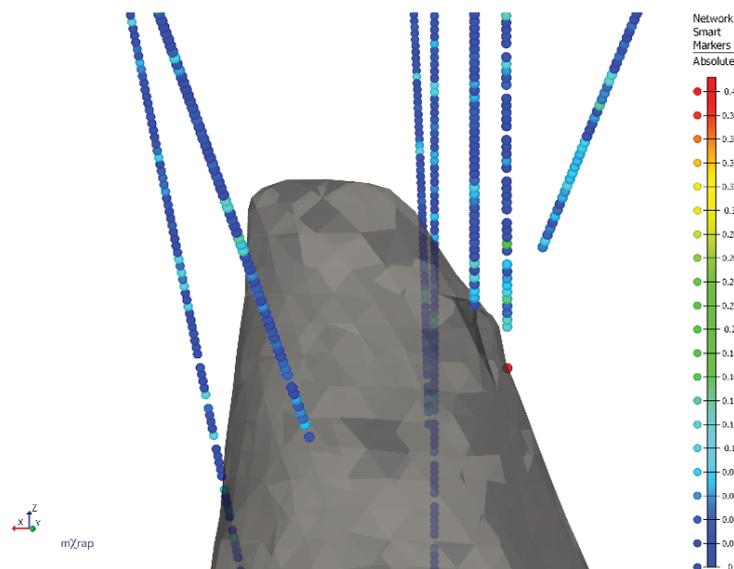


Figure 4 Array of Networked Smart Markers around the inferred cave back. Markers are coloured by RSSI (signal strength)

The NSMs can be programmed to communicate on a set schedule, which must be optimised to achieve the required frequency of data, whilst preserving the battery life of the markers. Results can be easily exported by site engineers without requiring post-processing. This has resulted in the array of NSMs becoming one of the most valuable systems for cave back monitoring at Carrapateena.

2.2.1 Limitations and learnings

The Networked Smart Marker system has been very successful as a cave back monitoring tool at Carrapateena. The marker signals can be easily exported and interpreted by site engineers, and ease of use for exporting and interpreting the data makes NSMs a valuable set of data for engineers to use on site.

During the installation period, it was essential to have good QA/QC (quality assurance/quality control) and records of what markers were installed in which hole, to ensure data quality and reliability for future interpretation. Occasionally, the NSMs may show erroneous data, and it is imperative to ensure that this is not due to the markers being in a different location than assumed. At Carrapateena, there is one string of Network Smart Markers that show erroneous data. This is assumed due to the presence of other monitoring systems in proximity, without which the potential cave interpretation may differ significantly. Care should always be taken to ensure good engineering rigour is applied to interpretation of the data, and to remember that all remote monitoring systems are not a direct measurement or observation of the cave. Cave changes are inferred through assuming the data correlates to physical changes in the rock mass at the point of measurement, however electronic systems can always be subject to other errors.

2.3 Beacons

Cave Tracker Beacons, also from Elexon Mining, were installed in an array above the footprint to monitor the cave back position and track material flow once beacons had entered the muckpile. Cave Tracker Beacons are grouted into the rock, and at set time intervals, an electric motor within the housing spins a magnet inside the beacon (Elexon Electronics 2016). This signal is then picked up by a fixed 3D array of detectors installed in the rock around the cave, allowing the detectors to track the 3D position of the beacons, even once they are in the muckpile (Elexon Electronics 2016).

For cave back monitoring at Carrapateena, beacons that have never moved are assumed to be outside the cave back. Once movement of a beacon is first detected, and if judged reasonable, it is interpreted to have fallen into the muckpile/mobilised zone, indicating cave growth through the original beacon location.

Depending on the beacon spin frequency and certainty in the data, the distance the beacon first moves can be related to the size of the airgap, although at Carrapateena it is not treated as a direct measurement. Once the beacon is in the muckpile, it is tracked as it flows down, and this data is used by geotechnical and cave flow engineers regularly.

Figure 5 shows the array of beacons originally installed around and above the Carrapateena cave back, at their original install locations.

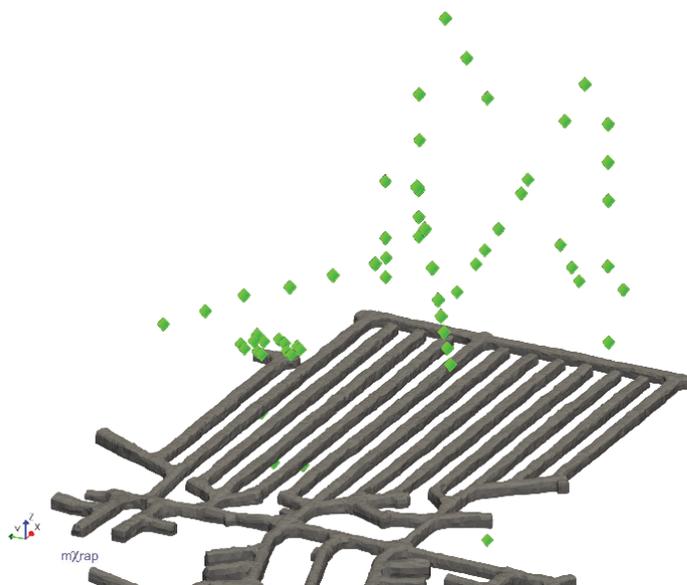


Figure 5 Cave Tracker Beacons installed above the sublevel cave footprint

2.3.1 Limitations and learnings

Whilst the beacons installed at Carrapateena have provided incredibly valuable data, particularly for flow monitoring, there are limitations to the current system and how it is employed at Carrapateena.

Firstly, tracking of the beacons is dependent on the array of detectors. Whilst the detector range is large (detecting beacons up to 180 m away), there are times where beacons fall outside of this range. With a limited number of detectors, some beacons are not able to be tracked in certain areas of the cave. Similarly, at these greater distances from the detectors, or if only a small number of detectors can be used to track a beacon, the potential error in location can be quite large. To detect if a beacon has moved, it often needs to move further than this potential error distance in order for movement to be reported reliably. Analysis of the beacon data at Carrapateena has evolved since the system was initially installed, and now the potential location error (90% confidence range) is plotted regularly over the beacon positions, represented as a box. This ensures all interpretation and review of the data is completed with this additional consideration in mind, providing information on the potential uncertainty on detected movement (or lack of movement).

An example of the ‘90% confidence boxes’ is shown in Figure 6, demonstrating the variability in the uncertainty of beacon positions at Carrapateena.

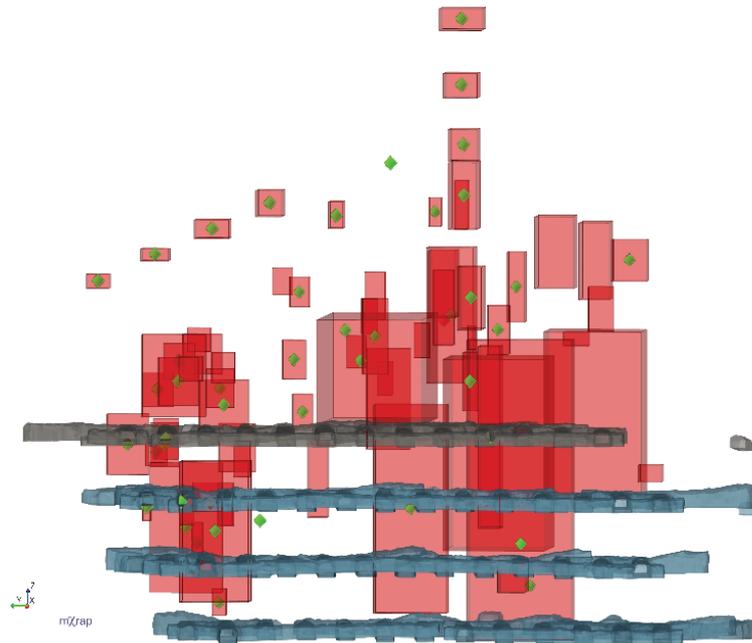


Figure 6 3D visual representation of beacon 90% confidence metrics, demonstrating the range in location uncertainty depending on proximity to and position within the detector array

Secondly, whilst the data that the beacons offer is outstanding in terms of monitoring flow in a way that has previously not been possible in the industry, there are limitations to the time frame with which decisions can be made. Unless a beacon moves a significant distance, it generally requires two to three ‘spins’ of the magnet for data processors to be confident that movement has occurred. If there is a substantial period between spins (for example one week), it could take two to three weeks for movement to be reported. For almost real-time cave back monitoring and reporting, this is undesirable. As each beacon is only one point of data and there are a limited number of beacons installed, they are generally a less useful tool for cave back monitoring than the NSMs. This is because (for Carrapateena) there are significantly more NSMs around the cave than beacons, and the time between a growth event occurring, and it being reflected in the monitoring data, is much shorter.

A reasonable amount of external post-processing is required to determine the 3D positions of beacons in and around the cave, based on the magnetic signals picked up by the detectors. Future, ideal scenarios for beacon monitoring would be that the processing is simplified or automated, and potentially able to be completed by site engineers without significant additional resourcing requirements. This would allow more timely data capture for analysis, and also allow interrogation of specific sites when required.

2.4 Microseismic system

The seismic system installed currently at Carrapateena consists of approximately forty 14 Hz (and several 4.5 Hz) triaxial geophones installed around the cave back and the active workings. The current M_{min} (system sensitivity) around the cave back is $M_L-1.3$ to $M_L-1.0$, meaning that tracking of microseismic activity around the cave back associated with the seismogenic zone is possible. An example of the system sensitivity in the area above the cave back is shown in Figure 7.

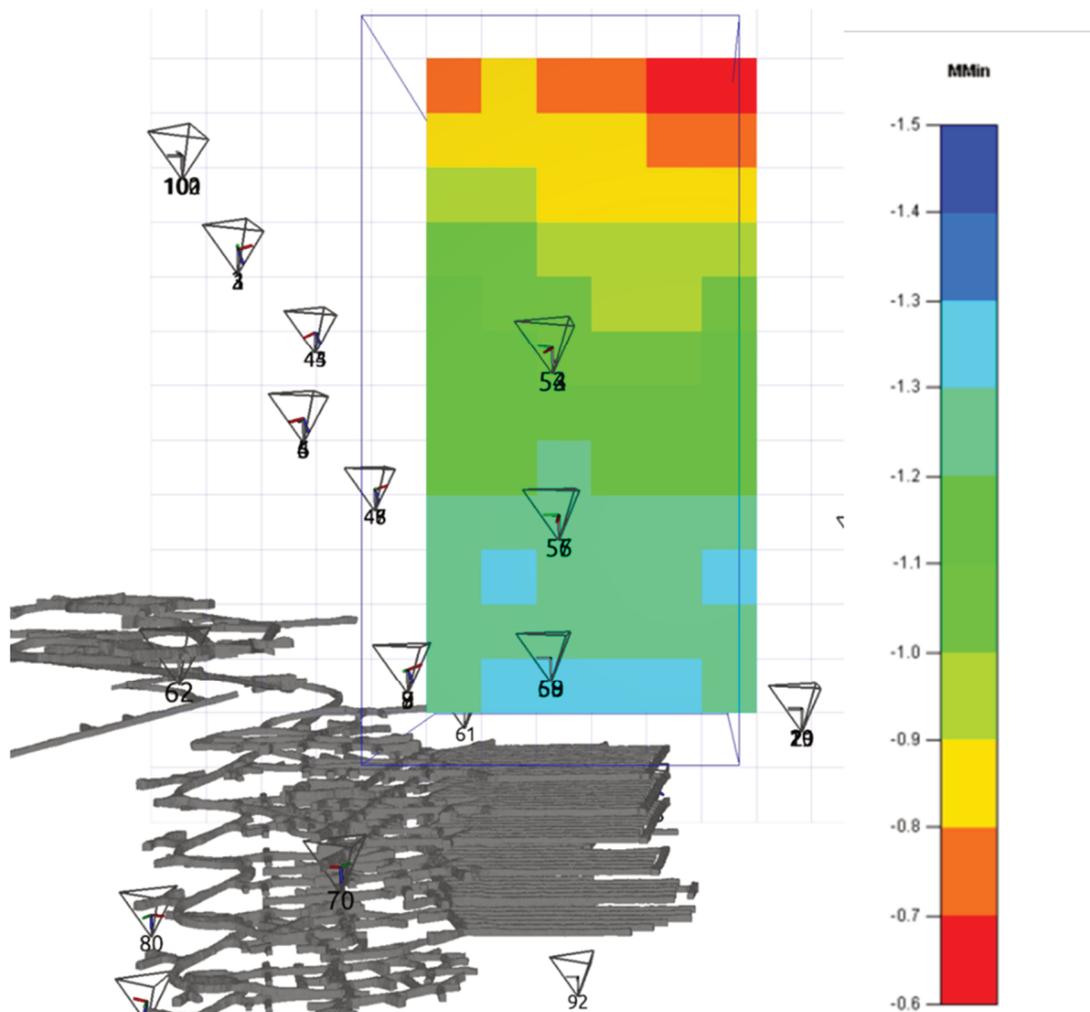


Figure 7 System sensitivity in area above cave back

The seismic system is a critical tool for monitoring the cave back at Carrapateena. Specific event details (e.g. location, local magnitude, energy index, source mechanism) are analysed, as well as a broader analysis and comparison of event rate, clustering locations and density, etc. Understanding and tracking of the events around the cave back can be an indication as to the cave seismogenic zone. Whilst seismic activity alone is generally not used to inform the cave back position, it is used to validate other monitoring methods, and provide an early indication that caving has taken place.

One benefit of the seismic monitoring in regard to cave back interpretation at Carrapateena is the almost real-time nature of the data, and the density of the dataset. Compared to all the other monitoring systems which provide limited, isolated points of data that must be interrogated and potentially post-processed, the seismic system allows engineers to view almost instant information over the entire volume being monitored. An increase in seismic event rate in a certain location, or a change in the location of seismic clustering, can indicate changes occurring around the cave back. Trends in seismic activity and seismic activity rate are also tracked, and can be linked to cave activities occurring, such as bogging in certain areas. An example of seismic activity rate and the link to bogged tonnes from the SLC is shown in Figure 8.

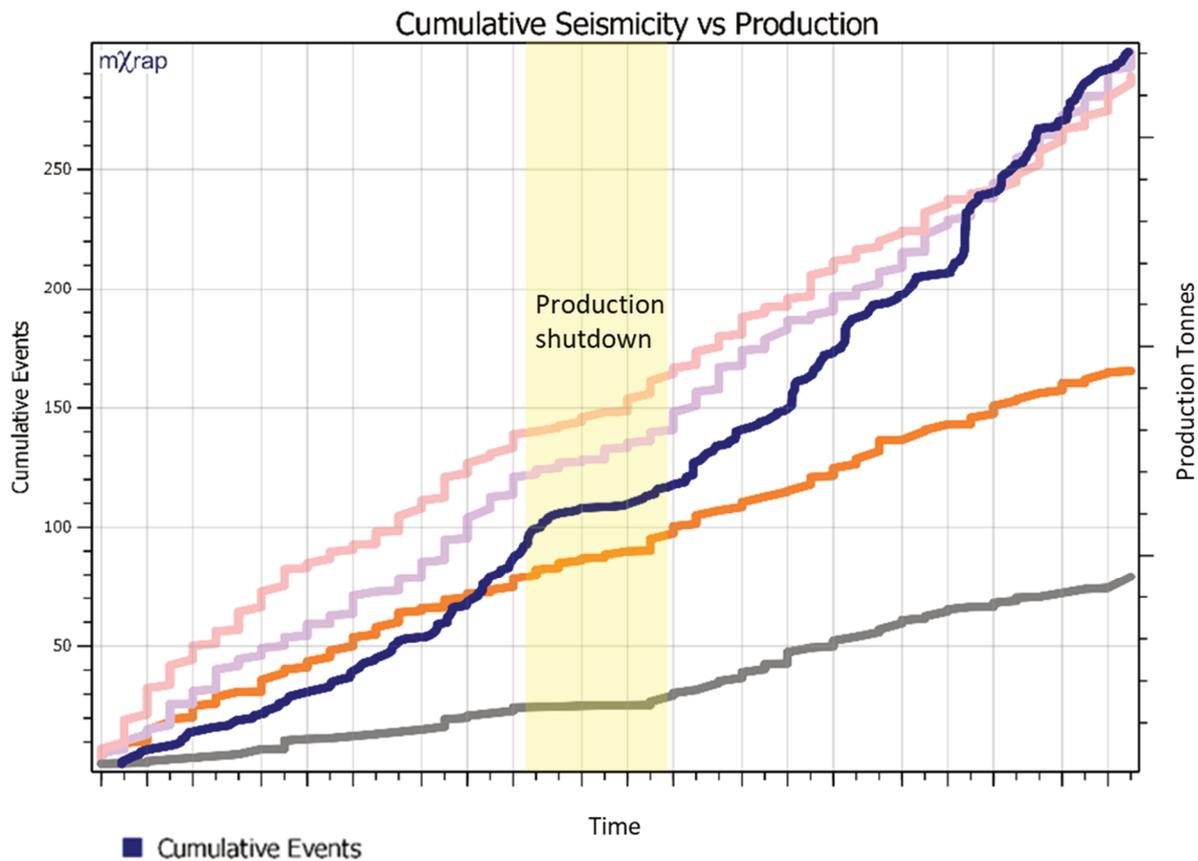


Figure 8 Cumulative seismicity around the cave back compared to production tonnes bogged per level. The correlation can be seen particularly in the highlighted period, which was a shutdown, where very few seismic events were recorded

2.4.1 Limitations

As discussed in the previous section, seismic activity alone is generally not used to inform cave back position, particularly cave growth. However, continued observation of seismic clustering in an area can be used to infer where the cave is not. This is due to several factors but particularly related to the potential location error for events around the cave, which in general is 10–20 m. Additionally, there is the uncertainty around the exact cause of an event. Generally, seismic activity around the cave back can be associated with stress-driven fracturing typical of the seismogenic zone, however the system can also pick up lower-energy single source events, such as impacts or falling rocks from the cave back. Of potentially more value for cave back monitoring than analysing the properties and location of specific single events, is monitoring more global trends of activity around the cave back, and how they evolve.

At Carrapateena, there was also some uncertainty as to how much seismic noise some of the cover sequence rock units would create, as the cave would be propagating through very weak sandstones and shales. If rock is soft and fails aseismically, a seismic system would be insufficient for tracking. This was theorised to be the case at Carrapateena, but so far there has been a seismic response to caving, although it differs between lithological units of varying stiffnesses.

A further limitation of the cave back seismic monitoring system at Carrapateena is the physical location of the sensors. In order to achieve precise seismic monitoring above the cave back, several sensors were installed in locations that were expected to be consumed by the cave in the future. This design was intentional in order to achieve the precision and data density required to monitor early cave activity; however, it does mean that some seismic sensors were installed sacrificially. As the cave grows and consumes further sensors, the sensitivity of the system may decrease, but remains sufficient due to an expanding array outside of the cave area. Additionally, it is expected that close to the surface, failure will be less stress-driven

due to the reduced depth and confinement, and less seismicity will occur. One benefit of the ‘sacrificial’ seismic sensors is that they provide an additional definitive data point for cave position when they are consumed, and due to the constant communication with the seismic system, often the exact time it was consumed can be found. This can be beneficial to correlate cave growth with specific events or activities.

2.5 Active tomography

As the Carrapateena cave is propagating through a large (280 m) unit of weak, interbedded shale, it was identified early in the monitoring design process that tracking the cave back through microseismic monitoring may be difficult within the shales. To collect additional data, several active source pneumatic ‘knockers’ were installed around the cave zone, which create a regular vibration pattern that gets picked up by the installed seismic system (geophones). The travel times of the vibrations from the source to each sensor can then be compared over time. Changes in the travel times could then be used to infer changes to the rock mass caused by the cave. This may be the result of cave growth forcing the raypath to change (i.e. lengthened to go around the cave), a decrease in seismic velocity associated with weakened rock mass caused by damage from cave propagation, or a potential increase in velocity associated with an increase in stress due to redistribution caused by cave growth in other areas.

2.5.1 Limitations

Practically, the use of the active seismic tomography for monitoring of the cave back at Carrapateena is limited to retrospective analysis only. The significant amount of post-processing required, as well as the uncertainty regarding exactly what the cause of a change to seismic travel times may be, makes it difficult to use to infer any changes to the cave back with a reasonable degree of confidence, in a timely manner.

Correlation in post-analysis has been found, with cave changes inferred through other monitoring methods able to be observed in the active tomography data.

2.6 Fibre-optic strain monitoring

Fibre-optic strain sensing is currently installed from the surface in three holes into the cave. At time of writing, the technology and data processing technique are still under research and development, in conjunction with Mining 3 and CSIRO. However, initial results have been promising. The fibre-optic cable is installed in holes that also have NSMs installed, and this has allowed a direct comparison of the data. Results from the fibre-optic monitoring have aligned with instances of the Networked Smart Marker signal strength change and particularly loss of signal (i.e. Networked Smart Marker falling into the cave due to growth of the cave back). An example of this is shown in Figure 9, where a string of NSMs recorded cave movement over a period of two weeks, which was also able to be observed in the fibre-optic data. The fibre-optic data analysis also shows strain to a more precise level, due to the sensitivity of the measurements, as well as having a continuous measurement rather than inferring signal strength change between points up to two metres away from one another.

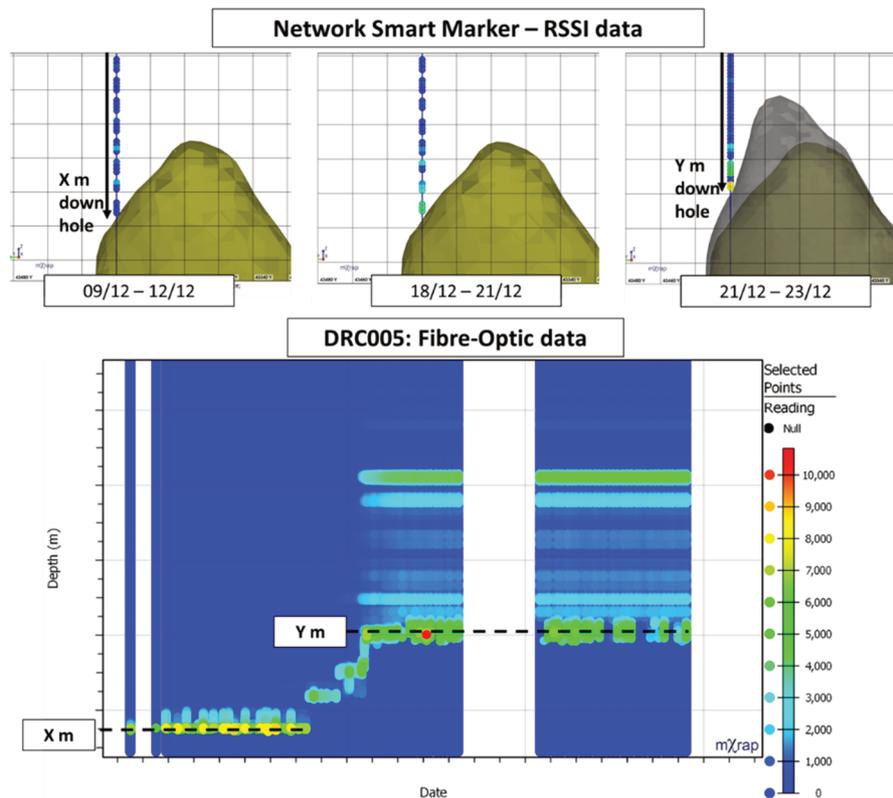


Figure 9 Networked smart marker observations over a two-week period correlating with fibre-optic strain data from the same hole

2.6.1 Limitations

As mentioned above, the system is still in development and at time of writing, data is received on an ad hoc basis (although this is improving quickly). A significant amount of external post-processing is required, which, as for all the monitoring methods, is one of the main limitations.

Additionally, further work is required to correlate the readings with actual measures of strain in the rock mass, as currently the strain measurement is used in relative terms only.

3 Data analysis

With the numerous and varied monitoring systems employed at Carrapateena, the quantity of data is very large. Systems were required to store, view, and analyse the data, as well as to provide a way to access and view all the data in one location. All the individual monitoring systems in place work together as the overall cave monitoring array, as being able to analyse and view the different data sets is critical in understanding the cave as an overall system.

At Carrapateena, the programs most used for this purpose are the Caving app in mXrap, developed by the Australian Centre for Geomechanics, and Leapfrog Geo.

3.1 mXrap

The site engineers have worked with the mXrap team to ensure all required data is able to be incorporated into the software and displayed in a useful and accessible way. The mXrap Caving app is able to incorporate all of the below:

- Solids files (i.e. mine plans and as-builts, structures, geology and lithology, drillholes).
- Production data, including all production firing and bogging data, with location and time attributes.

- Open holes and open hole dip data.
- Networked Smart Marker data.
- Beacons data.
- Recovered marker data.
- Seismic events (including display of source mechanisms, and clustering iso-surfaces).
- Fibre-optic data.
- Active tomography data (shown as raypaths).
- Seismic system (sensors).

All data can be viewed in 3D and analysed in multiple charts and other visual tools. Data is time-attributed, so toggling through time is simple and allows easy comparison and analysis of changes. Being able to view all the data in the one package makes it easy to analyse the data, make interpretations and conclusions, assess risk, and make engineering decisions regarding the cave.

3.2 Leapfrog Geo

Leapfrog Geo is used by site engineers for cave interpretation and data analysis. The program is predominantly used to generate a cave shape by viewing and analysing all monitoring data to infer the most likely position of the cave back and muckpile, then using the solid interpolation feature to generate a shape based on fixed constraints set by the engineer. This shape is then published to a central server each month, and it is sent out with geo-tagged comments to the senior team for cave shape review.

Leapfrog Geo is useful due to the large range of data formats that can be imported into the program, and most notably any data in 'csv' format can be imported and displayed in multiple ways. Interrogations and evaluations are also used, as well as the program being used to design new drillholes and monitoring holes.

4 Overall monitoring system

Overall, Carrapateena has many monitoring systems that all work in conjunction to allow the geotechnical engineers to understand the cave back and how it changes to a reasonably high level of confidence.

As with all geotechnical monitoring, particularly of large cave voids, there is an inherent level of uncertainty that cannot be avoided without significant cost. Engineering judgement is used to analyse the data and generate an interpretation of the cave shape, determining possible scenarios and ensuring hazards are understood in order to make engineering decisions.

There have been many learnings at Carrapateena regarding the location and density of monitoring systems in and around the cave. Budget constraints mean that the number of monitoring points can be limited, and each needs to be considered rigorously in relation to all other monitoring points, to ensure the maximum value can be attained.

Specifically at Carrapateena, the value of redundancy in the system has been a major learning. Having large areas of the cave back interpretation that are based on one monitoring point or method is not ideal, as this increases uncertainty and risk of misinterpretation. Where possible, having multiple systems to compare results in an area and corroborate any anomalous data is valuable.

Additionally, a rigorous process to determine the distribution and density of monitoring points is required. Cost may be a constraint, but care should be taken to design a monitoring system with considerations for all future scenarios of the cave, and not just the current status. For example, a dense array of markers in one location of the cave back was useful to monitor initial cave growth. However, the more mature cave requires monitoring in different areas. For this reason, the cave monitoring array at Carrapateena has evolved and changed over time.

5 Conclusion

The cave back monitoring array at Carrapateena is diverse, with various different methods used regularly to inform the position of the cave back, and the mobilised zone within the cave. There are benefits and limitations to all of the methods.

Predominantly, the most valuable methods to track the cave back position are open hole dipping with a wireline camera (supplemented with additional high-quality footage), and NSMs. The benefit of open hole dipping is that it is the only direct observation of the cave back and the muckpile. For NSMs, the value lies in the data density, and ease with which data can be retrieved by the site team with very little post-processing required. Additionally, microseismic monitoring forms a critical part of monitoring and cave management processes, allowing tracking of trends, analysis of influences on cave activity, and real-time indications and warnings of cave changes.

Cave Tracker Beacons are valuable for flow monitoring, provided a sufficient detector array is installed and maintained. However, the use of beacons to determine cave back position is less valuable than NSMs, due to the limited data points and delayed data.

Active seismic tomography using pneumatic 'knockers' shows promise, and has been correlated to known cave changes well, however currently the processing and uncertainty limit the system to being used in retrospective analysis only. The fibre-optic monitoring also has potential to be valuable and comparable to the NSM system (in the way both are used at Carrapateena), however further work is still being conducted to get to this point, particularly in regard to post-processing requirements.

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