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Hazard-aligned framework for interpreting cave geometry in block caving operations

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Abstract

In the management of large-footprint block cave mines, the interpretation of cave geometry is a fundamental input for assessing geotechnical hazards. However, a single definition of 'cave shape' is often insufficient to address the conflicting requirements of different geotechnical hazards. Operationally, a cave shape is commonly represented by the cave back, which is typically assumed to contain the mobilised zone or muckpile, while the space between the two, generated by drawing, may define a measurable airgap. This framework is appropriate for assessing connectivity-driven hazards, particularly airblast risk and airgap conditions. However, it does not capture the broader extent of yielding and rock mass degradation that may extend beyond the cave back. Consequently, when applied to seismic hazard assessment or surface breakthrough forecasting, it may lead to non-conservative interpretations.

This paper presents an integrated interpretation framework that explicitly distinguishes between the mobilised zone and the broader zone of rock mass damage (yielding), interpreting each not as a single cave shape but as distinct geometrical surfaces derived from the available monitoring data. Drawing on 2 case studies from a large-footprint caving operation, the framework demonstrates that damage propagation frequently extends vertically and laterally well ahead of material mobilisation. A data hierarchy is proposed where direct indicators (e.g. marker consumption, cave trackers movement, and open-hole breakthrough) constrain the mobilised boundary, while indirect indicators (e.g. seismicity and passive tomography) define the yielded zone. In this context, 'direct' and 'indirect' denote whether an observation constrains the mobilised boundary itself or the surrounding rock mass damage, rather than whether it is physically observed. By formalising this distinction, operators can maintain conservative controls for airblast risk without underestimating the spatial footprint of seismic hazards and breakthrough, ensuring that hazard management strategies are aligned with the governing physical mechanisms of each risk.

Keywords: *block caving, cave geometry interpretation, mobilised zone, yielded zone, geotechnical hazard management*

1 Introduction

Cave shape interpretation is one of the most important and most difficult tasks in block and panel cave mining (Brown 2003; Brady & Brown 2006). It underpins the management of airblast, cave breakthrough, seismic hazard, subsidence, draw strategy, and cave growth forecasting. In practice, however, cave shape is often treated as a single interpreted surface, despite the fact that different datasets respond to different parts of the cave system and different hazards are controlled by different physical boundaries.

This issue becomes more important in large-footprint cave mines where the hydraulic radius is well above the minimum required for cave initiation, and in mechanically mature cave systems, including panel caves and cave extensions, where rock mass damage, deformation and yielding can propagate substantially ahead

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of the fully mobilised cave. Under these conditions, a single interpreted cave shape may be adequate for some operational purposes, particularly for hazards controlled by void connectivity and flow, but it may underrepresent the broader rock mass response relevant to open hole damage-driven hazards such as seismicity, breakthrough and subsidence.

At Cadia East, cave interpretation practice has progressively evolved in response to this problem. Experience from PC2 and PC2-3 shows that the mobilised cave, the broader damage zone and the outer yielding response are related but not spatially coincident. Seismicity, degradation, passive tomography, marker behaviour, surface response and numerical modelling all indicate that the cave-induced rock mass response extends beyond the limits of the operationally interpreted mobilised cave. The cave-induced rock mass damage must be well understood and geometrically interpreted, as this has important implications for how cave growth should be interpreted and how different datasets should be weighted depending on the hazard being assessed.

The objective of this paper is to examine the evidence for decoupling between the mobilised cave and the broader yielded rock mass at Cadia East, and to propose a practical interpretation framework that distinguishes between these zones by defining them as operational zones and interpreting them as geometrical surfaces using the available monitoring data and analytical techniques where applicable. The paper argues that cave growth in large-footprint systems should not be represented solely by a single cave boundary. Instead, interpretation should distinguish between the mobilised cave relevant to connectivity-driven hazards and the broader yielded rock mass relevant to damage-driven hazards. This distinction provides a more mechanically consistent basis for cave tracking, hazard assessment and interpretation governance in mature cave systems.

2 Background: conceptual models of cave growth

2.1 Duplancic and Brady models

The conceptual framework most widely adopted in the caving industry was proposed by Duplancic and Brady (1999) and further detailed by Duplancic (2001), based largely on observations from the Northparkes E26 Lift 1 mine. The model describes 5 vertically stacked zones above the undercut: the caved zone, comprising mobilised material; an air gap; a zone of discontinuous deformation or loosening; a seismogenic zone characterised by active fracturing; and the surrounding rock mass responding elastically.

A key assumption of the classical model is that rock mass damage is greatest adjacent to the cave back and decreases progressively outward into the surrounding rock mass. This implies a continuous spatial coupling between damage development and material mobilisation. Although this assumption is useful as a first-order conceptual framework, it becomes less valid where cave growth is controlled by discontinuous damage propagation and fracture banding, as observed at Cadia East, which is representative of a large-footprint cave system.

It is also important to recognise the scale of the case from which this conceptual model was derived. Northparkes E26 Lift 1 was a relatively compact cave, mining the upper 460 m of the orebody with undercut footprint dimensions of 196 × 180 m. This indicates that the Duplancic framework was developed from a comparatively small cave operating under cave initiation and early propagation conditions in a virgin cave system, rather than from a large and/or mechanically mature cave system.

A further limitation of the Duplancic–Brady model is that the seismogenic zone, when used as an indicator of damage extent, is not a purely geomechanical boundary. In practice, it is partly a monitoring construct, the apparent extent of which depends on the geometry, sensitivity and performance of the installed seismic system. More generally, this limitation applies to any monitoring system: the resolution of the interpreted response is constrained by the density and inter-sensor spacing of the installed array. The Institute of Mine Seismology notes that interpretations of cave state derived from seismic data are influenced by the monitoring system and may not directly represent the full physical extent of rock mass response (Meyer 2023). The seismogenic zone defined from passive seismicity should therefore be treated as an incomplete proxy for damage extent rather than as a definitive mechanical boundary.

Most of the conceptual model, therefore, reflects the behaviour of Northparkes E26 Lift 1 under that specific geometrical and mining context. This point is important because the response of larger and deeper cave systems may differ materially from that inferred from a relatively compact cave near its caveability threshold. It is also important to recognise that the Duplancic–Brady model is a simplified two-dimensional conceptualisation; in practice no cave reproduces this idealised profile, and interpretation must be made from sparse data relative to the rock mass volume involved.

2.2 Non-linear damage progression and fracture banding

A key departure from the classical model is the recognition that damage progression ahead of the cave is not necessarily continuous or linear. Physical modelling studies using centrifuge testing by Cumming-Potvin (2018) showed that rock mass damage can advance episodically through discrete bands of intense fracturing oriented subparallel to the cave surface, a mechanism termed fracture banding. In these experiments, cave propagation occurred through a series of stepwise upward jumps from one fracture band to the next, rather than through gradual and continuous failure. The resulting damage profile ahead of the cave is therefore discontinuous, with local peaks in damage intensity associated with individual fracture bands rather than a smooth decay away from the cave back. Comparable examples of discontinuous tensile fracture banding, and their contrast with the idealised Duplancic profile, are presented by Kampa et al. (2024).

The field evidence examined by Cumming-Potvin (2018) is also important in the context of scale. The case studies used to support the fracture banding mechanism were all substantially deeper than Northparkes E26 Lift 1, spanning a depth range of about 800–1,400 m below surface, and all involved materially larger footprint systems. These included 2 deep block caves at approximately 1,200 m and 1,400 m depth, a cave developed at about 1,100 m depth beneath an earlier sublevel cave, and a large Swedish iron ore sublevel cave with its uppermost mining level at about 800 m depth. Footprint dimensions for these cases varied from approximately 70,000 m² to 140,000 m², further emphasising their larger scale relative to the Northparkes E26 Lift 1 case.

This contrast in scale is important because it indicates that the fracture banding mechanism was identified in cave systems that were not only deeper, but also materially larger and more mechanically mature than the relatively compact Northparkes Lift 1 case study. In these larger systems, cave propagation was observed under conditions of greater vertical extent, larger lateral span, and in some cases, interaction with pre-existing established caves. Accordingly, the observations reported by Cumming-Potvin (2018) extend the understanding of cave mechanics into conditions that are fundamentally different from those that underpinned the original Duplancic model.

2.3 Continuous subsidence and the upward propagation of deformation

A related concept from coal mining is continuous subsidence above longwall panels (Whittaker & Reddish 1989; Heritage et al. 2022). In that setting, surface deformation does not require a continuous open void extending from the extracted seam to surface. Instead, the overburden responds through progressive caving near the seam, fracturing and bed separation in the overlying strata, and distributed compression, sagging and settlement higher in the rock mass. The resulting surface subsidence is therefore the cumulative expression of a vertically distributed deformation field rather than the upward migration of a single open cave column. In longwall practice, this broader deformation envelope is commonly represented using the angle of draw concept, which defines the outward limit of observable surface response above the mined panel. Figure 1 illustrates this concept schematically, showing how the mechanically affected zone broadens upward from the mine workings to the surface.

This analogy is relevant to large-footprint cave systems because it shows that vertically continuous deformation can be transmitted through the rock mass without requiring continuous cave propagation in the strict sense of an unbroken airgap or flow-connected void. Coal subsidence studies likewise show that substantial surface movement may be governed by fractured and weakened strata outside the immediately caved zone.

Accordingly, the coal mining concept of continuous subsidence supports a broader mechanical interpretation in which the outer yielded or deforming rock mass can propagate well beyond the mobilised zone. This does not imply that block caving and longwall subsidence are mechanically identical, but it does provide a useful conceptual analogue: large-scale extraction can produce a vertically continuous ground response to surface even where the inner caved or mobilised zone remains geometrically limited. This is directly relevant to mature large-footprint cave systems, where deformation and yielding may extend substantially ahead of the flow-connected muckpile. The extent to which this analogue applies depends on rock mass strength and stiffness, footprint size and cave geometry: a larger footprint promotes upward-propagating yielding, whereas a small footprint with a self-supporting dome may remain closer to the classical model.

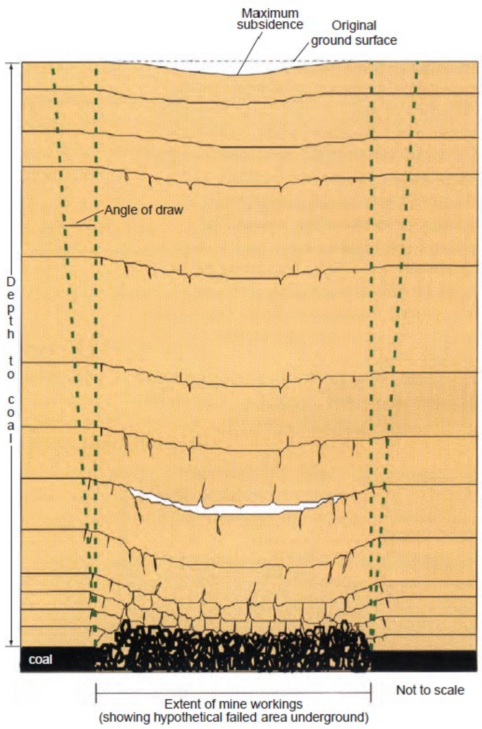


Figure 1 Conceptual subsidence profile above longwall coal extraction showing the angle of draw, maximum surface subsidence and the progressive upward widening of the deformation zone from the extracted panel to surface. Modified after Bauer (2008), based on Peng & Chiang (1984) and New South Wales Coal Association (1989)

2.4 Implications for large-footprint cave systems

The contrast between the classical Northparkes case and the cave systems examined by Cumming-Potvin, which include larger footprint areas, greater lift heights, or both, has an important implication: cave growth in large-footprint systems should not be assumed to follow the same simple relationship between cave back position, damage extent and material mobilisation implied by the classical model. In mature cave systems, particularly cave extensions, damage, yielding and deformation may propagate substantially ahead of the fully mobilised cave, and the boundaries controlling different hazards may therefore be non-coincident. Cave growth in these systems is better interpreted as progressive upward and lateral propagation of yielding driven by confinement loss rather than as the advance of a single discrete cave boundary. Although this paper emphasises large-footprint systems, comparable mechanisms can develop in smaller-footprint caves with high lift heights.

This non-linear view of cave propagation is also supported by later experimental and field studies. Heydarnoori et al. (2020) confirmed discontinuous damage development through base-friction modelling, showing that cave-induced deformation is highly dependent on the undercutting sequence. Field observations reported by Heslop (1976), Szwedzicki et al. (1999) and Carlson & Golden (2004) also describe fracture development, cyclic failure, and tensile cracking occurring ahead of, or beyond, the immediately interpreted cave boundary. Taken together, these studies indicate that cave growth in large-footprint systems is more appropriately understood as the interaction of multiple nested mechanical zones rather than as the upward advance of a single continuously evolving cave back.

A similar behaviour was observed during PC2 cave propagation at Cadia East, where seismicity, open hole damage, tomography, surface displacement and subsequent interpretation work demonstrated that rock mass yielding and damage extended materially beyond the traditionally defined cave shape. The PC2 case study also showed that large cave systems do not require the presence of a measurable airgap for damage to propagate to surface. Instead, surface expression may develop through the progressive upward migration of yielding, deformation and rock mass degradation ahead of the fully mobilised cave zone (muckpile).

2.4.1 Cave propagation and open hole evidence at PC2

Cadia East is a caving operation developed as a sequence of interacting caves. PC1 was established first, followed by PC2. The current PC2-3 and PC1-2 footprints are extensions within this mature caving system. PC2 was mined as a large-footprint cave and ultimately broke through into PC1. This case study draws on the PC2 experience, which motivated the interpretation framework presented in this paper.

During early PC2 production, draw was concentrated around the central footprint, as shown in the October 2015 cave interpretation in Figure 2. At that stage, the interpretation was still guided by open holes expected to intersect the inferred cave boundary. However, progressive hole dislocation occurred before any hole achieved a clear and defensible intersection with a zone that could be confidently classified as the cave back.

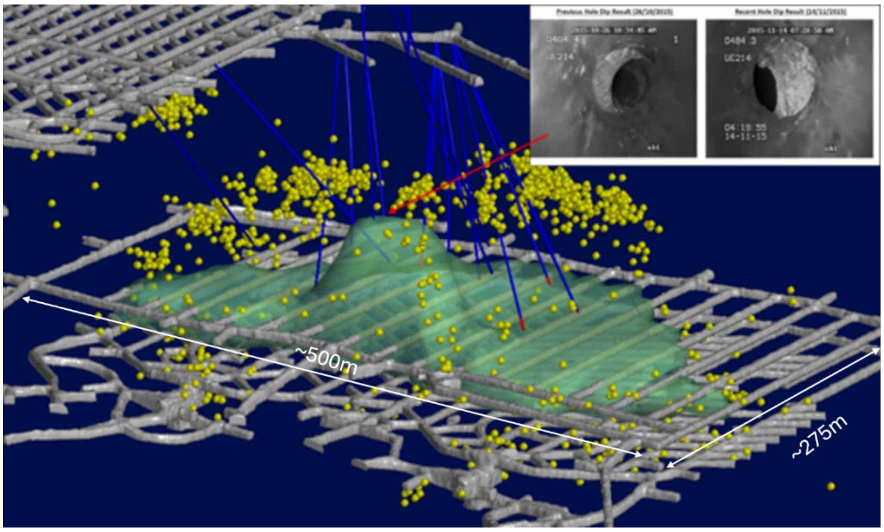


Figure 2 Seismic activity and mobilised cave shape interpretation for PC2, October 2015

By October 2016, as reflected in the cave interpretation shown in Figure 3, direct intersection of the so-called cave boundary had become increasingly difficult. Most drillholes were no longer able to reach the projected cave back position and instead exhibited clear evidence of progressive dislocation (Figure 3, where dislocated and blocked holes that failed to reach the projected cave back are highlighted). Subsequent attempts to drill additional surface holes to intersect the interpreted boundary encountered similar difficulties. In practical terms, direct confirmation through open hole intersection had become progressively unfeasible, as rock mass damage was propagating upward and outward at a non-linear rate relative to production and cave mobilisation.

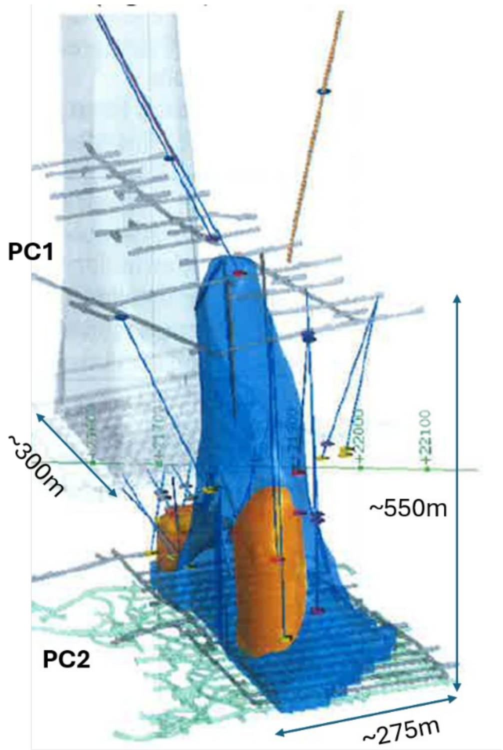


Figure 3 PC2 cave interpretation by October 2016

As PC2 ramped up to production across the whole available footprint, progressive damage within the rock mass column above the undercut led to widespread borehole deterioration, including dislocation and blockages, which prevented further deployment of the borehole camera. Surface prism monitoring showed that ground movement began between November and December 2016 (Figure 4), coinciding with the breakthrough of PC2 into PC1. This breakthrough marked a major shift in the interpretation framework. It became clear that an approach based on identifying a single cave boundary was no longer sustainable to manage the emerging geotechnical hazards associated with cave breakthrough.

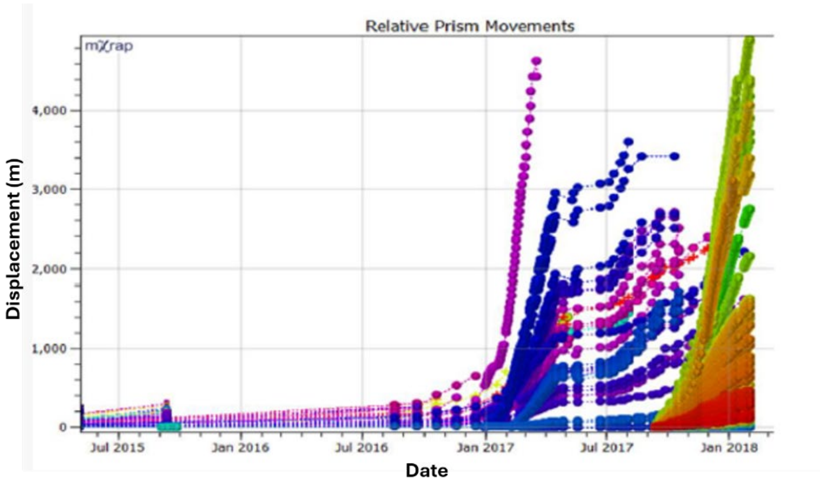


Figure 4 Relative surface prism movements at PC2, July 2015 to January 2018

By January 2017, there were 56 open boreholes drilled from the surface and 5050 level to monitor the PC2 cave. Based on the damage status of the 617 measurements taken from these 56 boreholes, 68% indicated either dislocation or borehole blockage (Figure 5). Only 8% of dipping achieved intersection with what was traditionally defined as the cave back boundary. It also became evident that rock mass damage above the footprint had reached the surface, as indicated by surface subsidence monitoring shown in Figure 4. To confirm full connection of the cave, some cave trackers were installed in the west flank of the cave from 5050 level; this proved to be difficult as many holes collapsed when approaching the western flank of the cave.

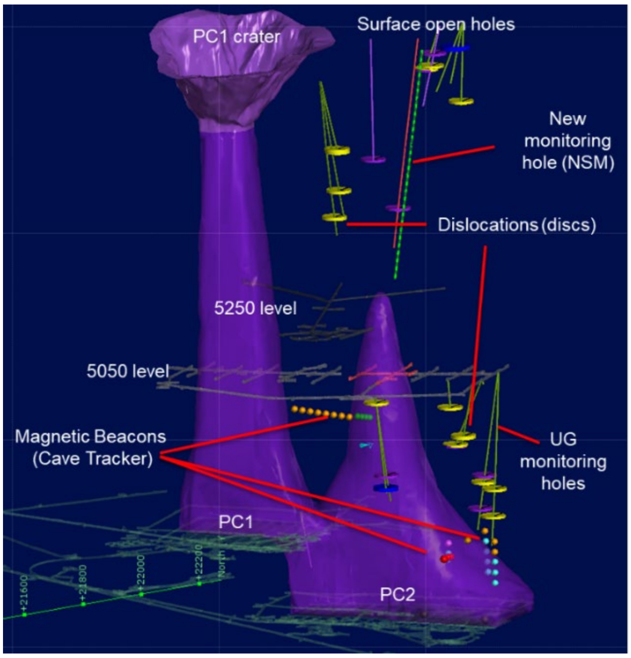


Figure 5 PC2 cave interpretation showing installed instrumentation for cave monitoring, November 2017

During September 2017, several cave trackers (magnetic beacons) were installed to monitor cave flow in the western flanks to confirm flow. Cave trackers installed at high elevations commenced detecting movement near November 2017, while surface prisms were already recording accumulated displacement of 0.5 m to more than 4 m (Figure 6). By February 2018, most cave trackers had moved vertically, confirming progressive mobilisation of the rock mass column.

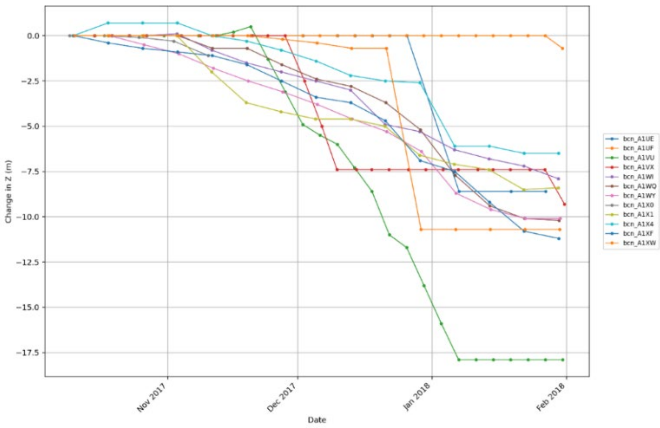


Figure 6 Cave tracker vertical displacement at PC2, November 2017 to February 2018

During November 2017, seismicity above the PC2 footprint showed that rock mass damage extended well beyond the interpreted cave zone. In response, cave shape interpretation evolved to incorporate the definition of a yielding zone, developed in collaboration with the Institute of Mine Seismology, and this was subsequently integrated into the cave interpretation assessment. An example of the seismic response and the corresponding yield zone geometry derived using this approach is presented in Figure 7. Cumulative surface displacement over the same period is shown in Figure 8.

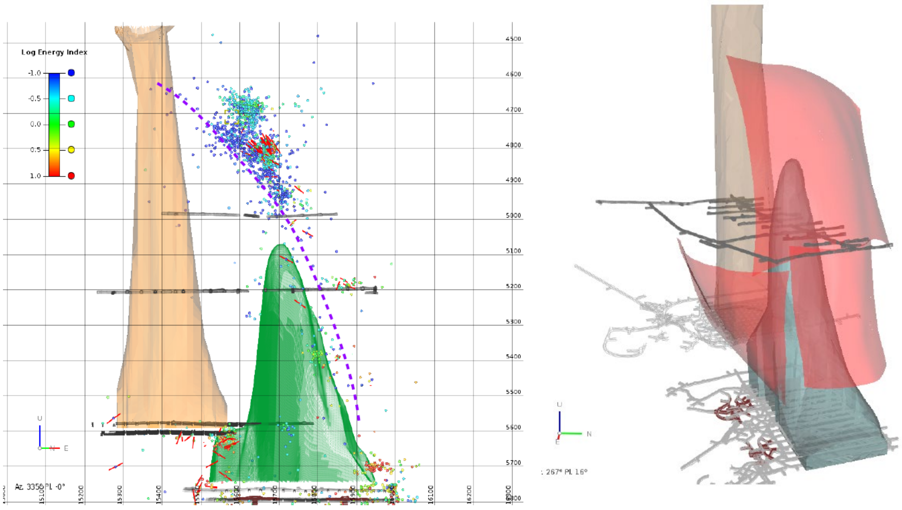


Figure 7 Seismic activity (left) and Institute of Mine Seismology's yield zone interpretation for PC2 (right), November 2017

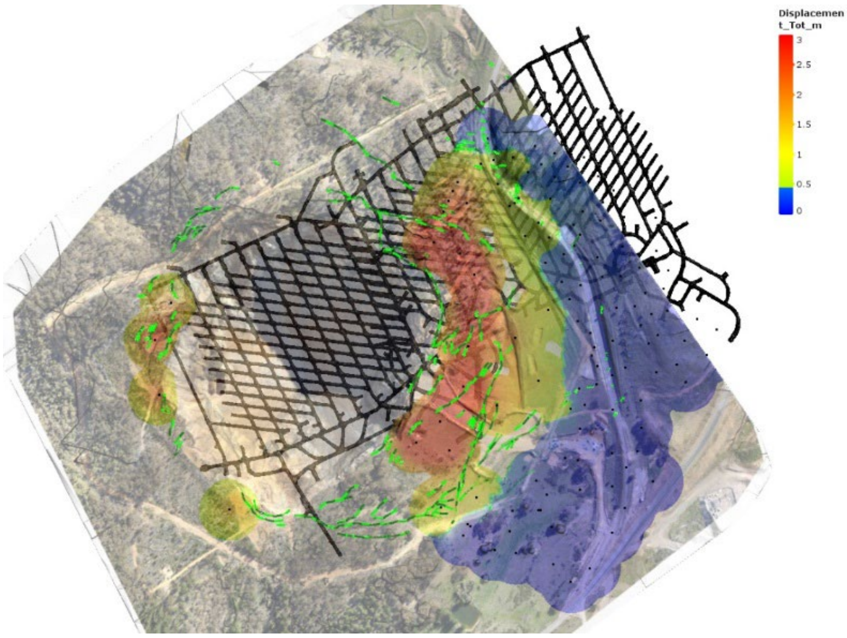


Figure 8 Cumulative surface displacement at PC2, November 2017

2.4.2 Key learnings and operational zone definitions

A key learning from PC2 cave interpretation was that defining a single cave shape was not feasible to manage all related geotechnical hazards for a large-footprint, tight-filled cave system. The interpretation strategy was therefore revised to match what was observed in the mine, with the intention that these learnings could be transferred to subsequent cave extensions such as PC2-3 and PC1-2.

The operational definitions for cave shape interpretation adopted in practice at Cadia East are as follows:

- The mobilised zone is the portion of the cave that behaves as muckpile, comprising a draw-connected broken rock mass in which confinement and interlock have been sufficiently reduced for the material to move, rearrange, and flow under gravity.
- The Dilation Zone is the transitional zone in which the rock mass has already undergone fracture opening and partial detachment but remains constrained by insufficient available void to permit

full gravity-driven collapse. It therefore represents a loosened but space-constrained rock mass, which can detach and transition into the mobilised zone once sufficient material is removed below.

- The yielded zone is the outer zone of inelastic rock mass damage. Within this zone, fractures may initiate or reactivate (including within locally concentrated fracture bands), structures may slip, and permanent deformation may accumulate, but the rock mass remains kinematically constrained and largely coherent at the rock mass scale. It therefore represents the outer envelope of cave-induced mechanical damage, beyond which the rock mass response remains predominantly elastic.

Together, these 3 zones provide a mechanically consistent framework for cave interpretation at Cadia East by distinguishing between mobilisation, transitional detachment under void constraint, and the broader outer envelope of inelastic rock mass response. An example of the yielded zone for PC2 is shown in Figure 9 for January 2018.

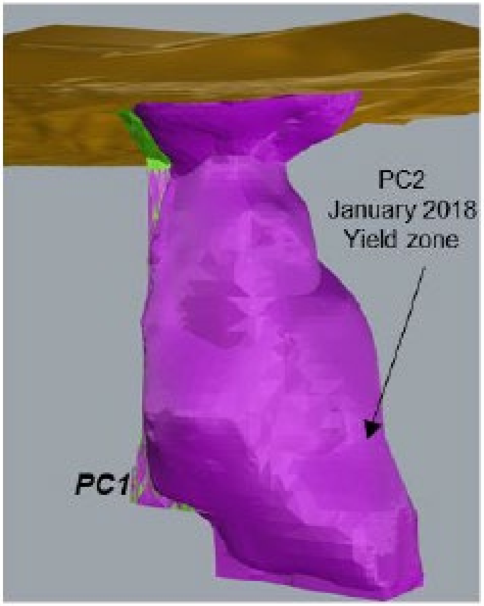


Figure 9 Yielded zone interpretation for PC2, January 2018

3 PC2-3 cave shape interpretation methodology at Cadia East

Experience from PC2 demonstrated that cave shape interpretation in large-footprint systems cannot be reliably represented by a single boundary. Observations of seismicity, open hole degradation, passive tomography and surface response showed that rock mass damage and yielding propagated substantially ahead of the mobilised cave, leading to ambiguity when attempting to define a unique cave shape for all purposes. These observations highlighted the limitations of a single-boundary interpretation framework and the need to distinguish between mobilisation and damage-driven processes.

At PC2-3, PC-2 learnings have been explicitly incorporated into the interpretation methodology. Rather than attempting to resolve a single cave boundary, the framework has been restructured to align with hazard-specific requirements, separating the definition of the mobilised cave zone from the broader yielded rock mass. This represents a deliberate shift from a descriptive interpretation approach towards a controlled, decision-driven system grounded in observed cave and rock mass behaviour.

Accordingly, cave shape interpretation at PC2-3 is implemented as a hazard-aligned methodology in which different interpretation products are developed for specific decision-making purposes. The reported cave shape is composed of 2 distinct zones: the mobilised zone and the yielded zone. The mobilised zone represents confirmed or strongly inferred connectivity to the cave void or airgap and is constrained primarily by direct indicators. This definition is conservative by design and is intended to support airblast risk management. In parallel, the broader rock mass response, including yielding, fracturing and stress redistribution, is recognised to extend beyond this boundary and is interpreted through a separate framework. The yielded zone is initially derived from integrated seismic analysis using model-based approaches and is subsequently refined through reconciliation with operational observations, including open hole damage observations (borehole dislocation and blockage), passive tomography and early indicators in Geo4Sight data. The final yielded zone therefore represents a reconciled interpretation of the evolving damage envelope rather than a directly observed boundary.

Table 1 Interpretation surfaces, hazards addressed and operational questions answered

Interpretation surface	Primary hazard(s)	Operational question
Mobilised zone	Airblast, airgap, draw control	Where is flow-connected material/is there an airgap?
Yielded zone	Seismic hazard, breakthrough, subsidence	How far has rock mass damage propagated and altered the stress field?

This approach reflects a shift from a purely descriptive interpretation of cave geometry towards a decision making–driven framework in which different boundaries are defined according to the governing mechanisms of each hazard, ensuring that interpretation remains aligned with both the available data and the requirements of risk management. The interpreted cave shapes for January 2026, comprising both the mobilised zone and the yielded zone, are shown in Figure 10.

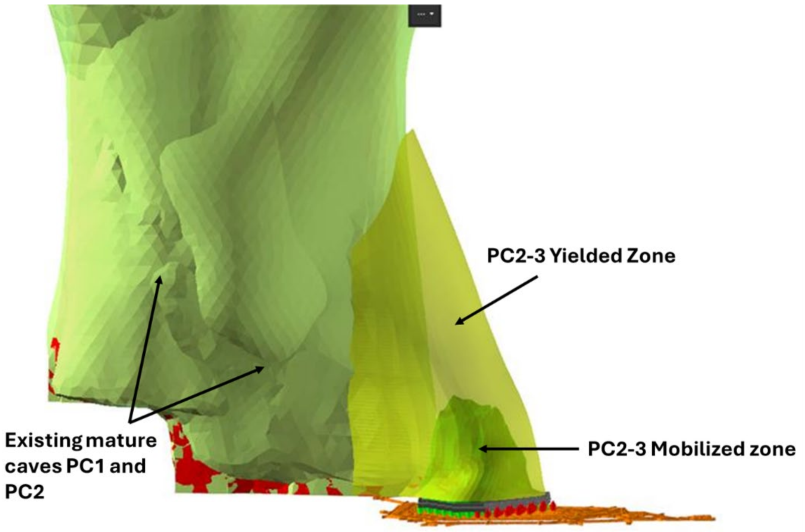


Figure 10 Yielded zone and mobilised zone interpretation for PC2-3, January 2026

Effective cave interpretation at PC2-3 is based on controlled integration of datasets with different levels of reliability and different physical meanings. Rather than attempting to eliminate uncertainty, the interpretation framework explicitly recognises and manages it through a defined hierarchy of data weighting and usage rules. Each dataset is assigned a specific role based on its ability to resolve either material mobilisation or broader rock mass response and is applied accordingly within the interpretation process. This ensures that uncertainty is not removed but explicitly managed – bound qualitatively by assigning a defined role to each dataset– maintaining consistency between the interpreted boundaries and their intended use in geotechnical hazard assessments.

3.1 Data weighting hierarchy and interpretation rules

Cave shape interpretation at PC2-3 is governed by a defined hierarchy of data weighting that distinguishes between indicators of material mobilisation and indicators of broader rock mass degradation evolution. This hierarchy ensures that each dataset is applied in a consistent manner with its physical meaning and level of reliability and prevents inappropriate advancement of interpretation boundaries based on ambiguous or indirect evidence. In this paper, indicators are classed as direct or indirect with respect to mobilisation: direct indicators confirm draw connection to the cave void (e.g. marker or beacon consumption and open hole breakthrough), whereas indirect indicators (e.g. seismicity, tomography, open hole dislocation and surface deformation) evidence rock mass damage but do not by themselves demonstrate connectivity; the classification refers to what each indicator constrains, not whether it is physically observed.

In practice, the interpretation follows 6 steps:

1. Establish the mass balance framework defining plausible cave growth.
2. Apply direct mobilisation indicators (marker or beacon consumption and verified open hole breakthrough) to constrain the mobilised zone and update the HOD/HOC (height of draw/height of cave) ratios.
3. Derive the initial yielded zone from integrated seismic analysis.
4. Refine the yielded zone by reconciliation with open hole damage, passive tomography and Geo4Sight data.
5. Verify both zones against FLAC3D numerical modelling.
6. Cross-check consistency between zones and against historical measured values.

Table 2 Data weighting hierarchy used in PC2-3 cave shape interpretation

Dataset	Constrains	Weight/role
Mass balance/production	Mobilised (maximum extent)	Bounding
Marker/beacon consumption; open hole breakthrough	Mobilised boundary	Highest: only data permitted to advance the mobilised boundary
Open hole damage (dislocation, blockage, air communication)	Yielded zone	High
Seismicity/passive tomography	Yielded zone	Moderate–high
Geo4Sight response away from cave	Yielded zone	Low: validation only
FLAC3D numerical modelling	Both	Verification only: never advances mobilised

At the highest level of confidence, the mobilised zone is interpreted primarily from mass balance, which provides the spatial framework for cave growth. Direct indicators of connectivity to the cave void, including confirmed consumption of Geo4Sight markers or magnetic beacons and verified open hole breakthrough, are then used as local high-confidence constraints on that interpretation. Where present, these observations provide the only basis for updating the HOD/HOC ratios. This distinction is fundamental to maintaining a conservative interpretation for airblast hazard assessment and to avoid conflation between rock mass damage and true mobilisation.

Indirect indicators, including seismicity (notably the low energy index events characteristic of caving), seismic imaging, open hole damage states (including dislocation, blockage and air ‘breathing’) and surface deformation, are not used to advance the mobilised zone. Instead, these datasets are interpreted as evidence of yielding, fracturing and stress redistribution within the surrounding rock mass and are therefore used to inform the definition of the yielded zone. This distinction reflects the recognition that rock mass damage may propagate substantially ahead of the flow-connected cave without implying the presence of a void or airgap.

Within this group, not all indicators carry equal weight. Open hole damage, including dislocation, blockage and air communication, provides direct in situ evidence of progressive rock mass degradation and is therefore assigned higher weighting in defining the extent of the yielded zone. In contrast, Geo4Sight marker response, while reliable for identifying interaction with the mobilised zone, has limited capability to resolve progressive damage within the rock mass, particularly in areas away from the cave where deformation is more diffuse. As a result, Geo4Sight data are used primarily for validation and consistency checks rather than as a primary constraint on yielded zone geometry.

Production data and mass balance calculations provide spatial coverage and volumetric constraints on cave growth and are used to assess the plausibility of interpreted geometries. Within this framework, they are treated as bounding tools rather than direct indicators of mobilisation, defining the maximum plausible extent of cave development in areas lacking direct observational constraints and supporting conservative airblast assessment.

Numerical modelling results, including FLAC3D simulations, are used as a verification tool for mobilised and yielded zones interpretations. Model outputs provide physics-based estimates of deformation, damage distribution and stress redistribution, and are used to assess the plausibility and consistency of the interpreted damage envelope, particularly in areas affected by limited monitoring coverage. Numerical modelling is not used to define or advance the mobilised zone under any circumstances and is only applied within the context of understanding and constraining the broader rock mass response.

Together, this hierarchy establishes a set of interpretation rules that govern how each dataset can influence the final cave shape. Direct indicators are used to define and constrain the mobilised zone, while indirect and model-derived indicators are used exclusively to construct and refine the yielded zone. By maintaining this separation, the interpretation framework ensures that each boundary remains aligned with the physical processes it is intended to represent and with the hazard it is used to assess.

3.2 Construction of the mobilised zone

Primary constraints on the mobilised zone are provided by confirmed Geo4Sight marker or beacon consumption and verified open hole breakthrough demonstrating physical interaction with the cave void. These observations provide local, high-confidence constraints on the cave back position and are the only data types permitted to advance the mobilised boundary. This rule ensures that the interpreted cave shape remains directly tied to confirmed or strongly inferred mobilisation.

In areas where direct indicators are absent, the mobilised zone is not advanced on the basis of indirect observations. Instead, interpretation is guided by consistency with neighbouring constrained areas, conservative mass balance limits and continuity of cave geometry. This approach avoids extrapolation of the cave boundary into regions where connectivity has not been demonstrated.

Production data and mass balance calculations form the primary basis for interpreting the maximum plausible extent of mobilisation and the potential presence of an airgap within the cave. Direct indicators of connectivity, such as marker consumption and verified open hole breakthrough, are used to establish and conservatively update the HOD/HOC ratios, which are then applied to extrapolate point-based observations across the broader cave surface. Updates to these ratios are made only when supported by multiple confirming measurements and by consistency with historical measured values. Initially, PC1-derived ratios were adopted, with progressive refinement as PC2-specific data became available.

The resulting mobilised zone is therefore a conservative representation of the flow-connected cave, intentionally biased towards underestimating the extent of mobilisation. This ensures that airblast hazard assessments remain conservative and that the interpreted cave shape does not overstate the degree of connectivity within the rock mass.

Figure 11 presents a representative interpretation from the PC2-3 RMP (rolling monthly plan) cycle, illustrating the spatial relationship between direct indicators of connectivity, indirect indicators of rock mass response, and volumetric constraints derived from the mass balance. This integrated view highlights the distinction between confirmed mobilisation and the broader zone of rock mass damage and demonstrates how the mobilised cave is conservatively constrained within the envelope of available data.

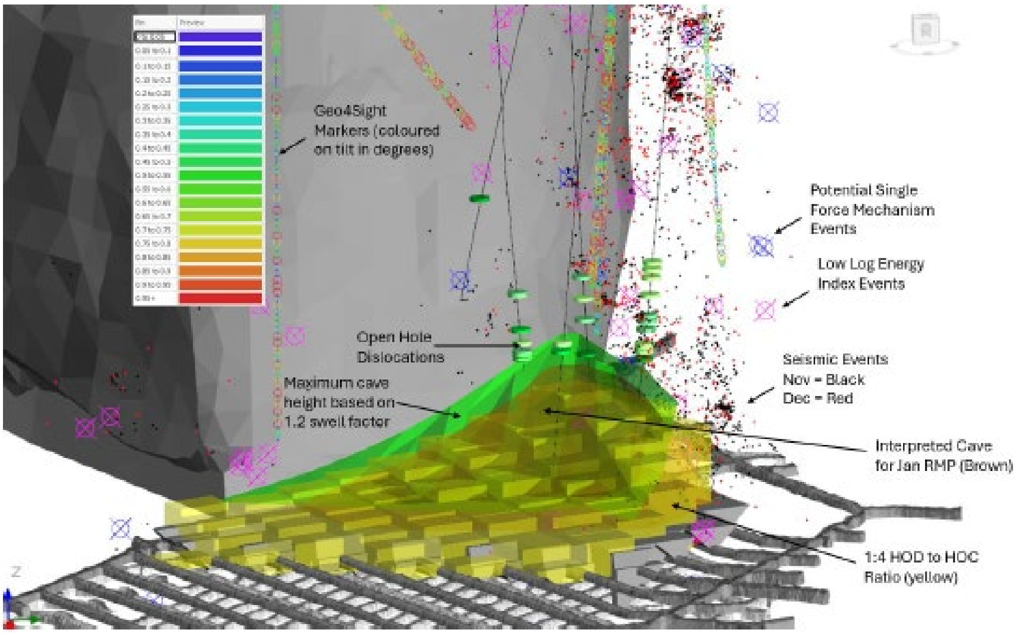


Figure 11 Integrated interpretation of PC2-3 cave geometry showing direct indicators of mobilisation (open hole breakthrough and marker response), indirect indicators of rock mass damage (seismicity and open hole dislocation) and volumetric constraints from mass balance, used to conservatively define the mobilised zone within the broader damage envelope

3.3 Construction of the yielded zone

The yielded zone represents the outer extent of rock mass damage associated with cave propagation, including yielding, fracturing and stress redistribution ahead of the mobilised cave, analogous to the excavation damage zone concept described for brittle rock (Perras & Diederichs 2016). Unlike the mobilised zone, which is constrained by direct indicators of connectivity, the yielded zone is constructed through the integration of indirect datasets and model-based interpretation methods and therefore reflects the broader mechanical response of the rock mass rather than a directly observed boundary.

At PC2-3, the initial geometry of the yielded zone is defined using integrated seismic analysis. This includes the application of structured interpretation frameworks that combine event locations, source parameters, source mechanisms and travel-time tomography to approximate the spatial extent of rock mass damage. These methods provide a volumetric, physics-informed estimate of the evolving damage envelope and allow the outer boundary of the yielded zone to be tracked independently of the mobilised cave.

This initial interpretation is subsequently refined through reconciliation with operational observations. Open hole behaviour, including dislocation, blockage and air communication, provides direct evidence of rock mass degradation and is used to validate or adjust the interpreted extent of the yielded zone. Similarly, Geo4Sight marker response, while primarily used to constrain the mobilised zone, provides additional context on deformation and loss of confinement near the cave back and supports consistency checks between seismic-derived interpretations and observed behaviour.

The reconciliation process is essential to ensure that the yielded zone remains consistent with the actual mechanical response of the rock mass. It allows model-derived interpretations to be adjusted where required, particularly in areas affected by monitoring limitations, geological variability or reduced data coverage, and avoids over-reliance on any single dataset. The final yielded zone therefore represents a reconciled interpretation that integrates seismic analysis, operational observations and engineering judgement into a single, coherent geometry. The surfaces are not generated by a formal averaging algorithm; rather, they are reconciled through a qualitative, evidence-weighted interpretation process applying the hierarchy in Table 2.

Figure 12 presents the spatial relationship between seismic activity associated with PC2-3 mining and the distribution of open hole dislocation above the cave, illustrating the extent of rock mass damage and the development of the yielded zone beyond the limits of the mobilised cave.

An important characteristic of the yielded zone at PC2-3 is that its evolution is not constrained by the advance of the mobilised cave. Seismic observations and successive interpretations demonstrate that the yielded zone may propagate laterally and vertically beyond the limits of the flow-connected cave, reflecting the independent progression of damage and stress redistribution within the rock mass. This behaviour is also consistent with observations of a tight-filled cave system, where the availability of space limits mobilisation while damage continues to develop.

This behaviour reinforces the need to treat the yielded zone as a distinct interpretation product, rather than as an extension of the mobilised cave boundary and highlights that cave propagation in large-footprint systems is governed by both mechanical damage evolution and the availability of space for mobilisation, which do not necessarily evolve concurrently.

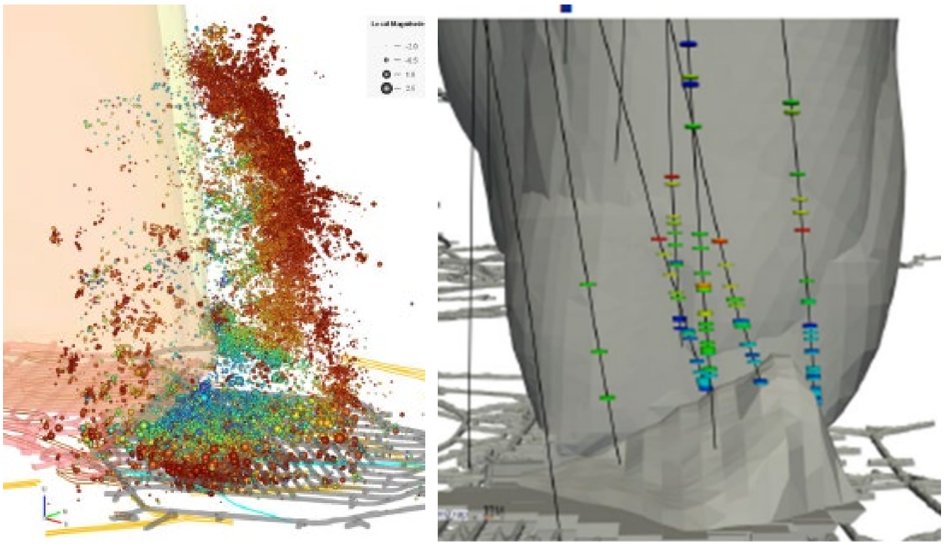


Figure 12 Seismic activity and open hole dislocation defining the yielded zone at PC2-3

Figure 13 presents the numerical model used as the final step in the interpretation of the yielded zone at PC2-3, illustrating the distribution of rock mass damage associated with caving and providing a physics-based constraint to validate the extent of damage extending beyond the mobilised cave.

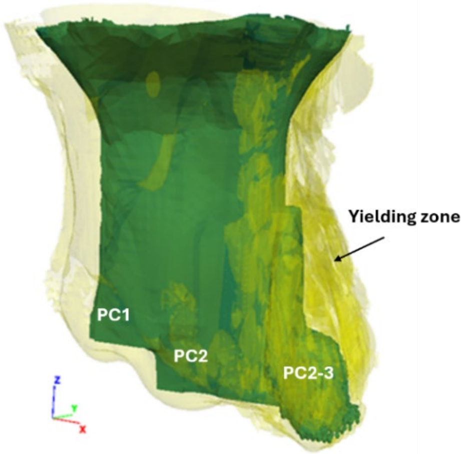


Figure 13 Numerical model simulation of rock mass damage development at PC2-3. The mobilised zone is shown in green (MassFlow mobilised markers) and the yielded zone is shown in yellow (total strain iso-contour of 5e-3)

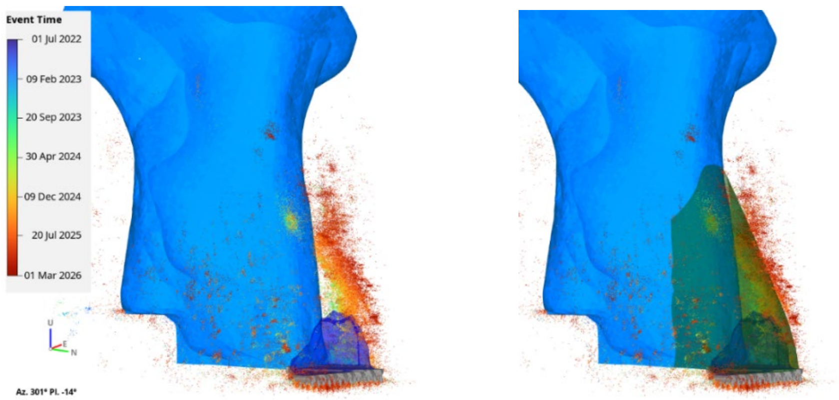
4 Evidence for non-coincident cave boundaries

The evidence presented in this section is not intended as an independent validation of each interpreted boundary where the same dataset contributed to its construction. Rather, it documents the observations that motivated and constrained the interpretation framework and shows how multiple datasets were reconciled to avoid reliance on any single indicator.

4.1 Seismic response and yielded zone development

Seismic monitoring provides a primary indicator of rock mass damage and stress redistribution associated with cave propagation. At PC2 and PC2-3, the spatial distribution of seismic events extends well beyond the interpreted mobilised zone, defining a broader seismogenic volume associated with yielding and fracture development. Low energy index events and other caving-related seismic signatures are consistently observed ahead of the cave back, indicating progressive rock mass damage prior to material mobilisation. In addition, seismic tomography shows reductions in wave velocity consistent with damage accumulation and loss of confinement (Jaimes et al. 2025), further supporting the presence of a volumetric yielded zone extending beyond the flow-connected cave.

An example of seismic activity associated with PC2-3 production, together with the interpreted mobilised zone and yielded zone, is presented in Figure 14.



(a) (b)

Figure 14 Seismicity associated with PC2-3 production, shown relative to the (a) interpreted mobilised zone and (b) interpreted yielded zone

4.2 Open hole behaviour and damage propagation

Open hole monitoring provides direct in situ evidence of rock mass response and offers valuable insight into the progression of damage around the cave. Observations across PC2 and PC2-3 consistently show progressive dislocation, blowouts, blockage and deformation of boreholes, reflecting the development of a failure zone within the surrounding rock mass. These observations demonstrate that rock mass damage can extend beyond the zone of confirmed mobilisation and form part of the broader response to caving.

In addition to mechanical degradation, open holes commonly exhibit dynamic behaviour such as air ‘breathing’, indicating pressure communication within the rock mass. These responses provide further evidence of evolving connectivity and permeability within the damaged zone and are consistent with the progressive development of the yielded zone during cave growth. Breathing behaviour is frequently observed in holes without confirmed breakthrough, reinforcing that damage and pressure communication can develop as the rock mass continues to deteriorate.

Figure 15 illustrates the spatial distribution and progressive dislocation of selected open holes relative to the interpreted cave geometry at PC2-3. The colour-coded markers represent successive observations along each hole, highlighting the evolution of deformation, displacement and loss of alignment with depth. The figure provides a direct visual representation of how borehole conditions degrade as they approach the cave influence, with increasing dislocation and clustering of observations in zones of elevated damage.

This visual evidence supports the observed behaviour that open hole response reflects progressive rock mass degradation rather than a discrete boundary, and demonstrates how damage develops and accumulates ahead of the mobilised cave. It also highlights the variability in hole response and accessibility, reinforcing the need to interpret open hole data within the broader context of rock mass behaviour rather than as a standalone indicator of cave position.

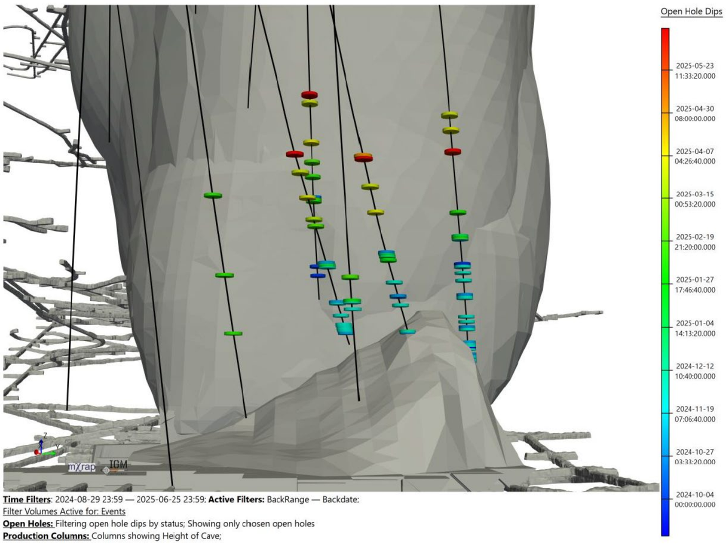


Figure 15 Open hole dislocation and damage progression relative to interpreted mobilised cave geometry at PC2-3

4.3 Surface response and upward propagation

Surface monitoring provides important constraints on the upward propagation of rock mass damage within the cave column. At Cadia East, observations from PC2 demonstrated that surface response, including subsidence and cracking, can develop as a result of progressive yielding and deformation propagating ahead of the mobilised cave, without requiring direct connection to an open void.

At PC2-3, no significant surface deformation has been observed to date, consistent with the current cave development stage, where the yielded zone has not yet reached surface. However, this does not mean damage is limited to the mobilised zone. Seismic and open hole observations indicate that yielding and rock mass degradation are developing ahead of the cave back. Surface monitoring is therefore interpreted as a lagging indicator of cave propagation, controlled by the evolution of the yielded zone rather than the position of the mobilised zone.

5 Conclusion

Cave shape interpretation in large-footprint block caving systems cannot be adequately represented by a single boundary. Observations from Cadia East demonstrate that rock mass damage, yielding and stress redistribution propagate substantially ahead of the mobilised zone, resulting in non-coincident boundaries between material mobilisation and broader rock mass deterioration. Critically, these zones are most useful when interpreted not as a single descriptive cave shape but as distinct geometrical surfaces of mobilisation and damage, allowing each hazard to be assessed against the boundary that actually governs it.

The framework presented in this study addresses this limitation by explicitly distinguishing between the mobilised zone and the yielded zone. The mobilised zone, defined using direct indicators of connectivity, provides a conservative and operationally robust basis for airblast hazard assessment. In contrast, the yielded zone, derived from integrated seismic analysis and refined through reconciliation with operational observations and numerical modelling, captures the extent of rock mass damage relevant to seismic hazard evolution and breakthrough processes.

A structured data weighting hierarchy, summarised in Table 2, is central to this approach. Direct indicators are used exclusively to constrain the mobilised zone, while indirect and model-derived indicators are used to construct and refine the yielded zone. This separation prevents conflation between mobilisation and damage, ensuring that each boundary remains aligned with the physical process it represents.

Evidence from seismic response, open hole behaviour and surface observations supports the interpretation that damage propagation evolves independently of the mobilised cave and should be treated as a distinct process. Surface response, where present, is shown to be a lagging indicator of this progression and is not required to define the extent of the yielded zone.

By aligning cave shape interpretation with hazard-specific requirements, the proposed framework provides a more robust and defensible basis for geotechnical risk management. It enables conservative control of airblast hazard while avoiding underestimation of seismic hazard and breakthrough potential, ensuring that interpretation remains consistent with both observed behaviour and the governing mechanisms of each hazard.

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Disclaimer

The technical information, geomechanical interpretation frameworks, operational definitions, and data weighting hierarchies presented in this paper are site-specific to the Cadia East operations and have been developed solely for internal operational management, academic discussion and industry knowledge sharing. This paper contains certain forward-looking observations and structural forecasting models regarding rock mass behaviour, seismic hazard evolution and cave growth propagation. These statements and models are based on current data, monitoring configurations and geological assumptions; actual geomechanical responses, subsidence trends and operational outcomes may differ materially due to localised geological anomalies, changes in draw sequence or monitoring system limitations. Newmont Corporation and the authors make no warranties, express or implied, regarding the applicability or safety of these methodologies when applied to other mining operations or distinct geological environments. Nothing contained herein constitutes investment, financial, or legal advice, nor should it be relied upon to evaluate the financial performance or market securities of Newmont Corporation.

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