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Challenges encountered in high-lift block cave extensions and the lessons learned: experience from the Padcal Mine, Philippines

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Abstract

The Padcal Mine in northern Philippines has operated using block caving since 1963 and continues to extend production into deeper and peripheral ore zones through high-lift block cave development. Since 2021, recurring rockburst events have been recorded during the development and early commissioning of the 798 mining level blocks, particularly within high-lift extensions located at the margins of the active cave footprint. These areas are characterised by abutment stress concentrations and complex stress redistribution associated with staged cave expansion.

This paper documents the challenges encountered during the development and commissioning of high-lift block cave extensions, with emphasis on seismic response, ground support performance, dilution control, and block development layout and sequencing. Lessons learned from Padcal highlight the critical role of abutment stress management, the importance of drawpoints connectivity, the limitations of conventional support systems under dynamic loading, and the need for adaptive draw control, undercutting, and development strategies. Mitigation measures implemented include enhanced active support reinforcement, blasting deferment protocols, draw control strategies, and the use of isolation crosscuts to manage cave expansion risks and to achieve successful block commissioning.

The outcomes offer practical, experience-based guidance for planning, commissioning, and operating high-lift block cave extensions in similarly stressed and seismically active environments.

Keywords: *block caving, high-lift cave extension, rockburst, seismic response, ground support, abutment stress, dilution control*

1 Introduction

The Padcal Mine, operated by Philex Mining Corporation, exploits the Sto. Tomas II copper–gold porphyry deposit in Benguet, Philippines. Following a transition from open pit to underground block caving in 1963, the operation has progressively evolved, notably shifting to mechanised load-haul-dump extraction in 1994 to manage increasingly competent rock masses at depth. Similar to the E26 Lift 1 North expansion at Northparkes, Padcal is expanding its block cave beyond its original footprint to extract peripheral, high-lift virgin columns with no overlying mining levels. While this strategy extends the life of mine and maximises the economic viability of massive, lower-grade orebodies, expanding the cave footprint at depth introduces complex geotechnical and inherent operational constraints. Primary among these are high abutment stresses, mining-induced seismicity, early entry of dilution, and the disruption of existing infrastructure during cave development and expansion. Sustaining safe and efficient production under these dynamic conditions requires continuous study and improvement of Padcal's cave design and extraction sequencing.

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2 Mine and block context

To maximise the economic viability of lower-grade orebodies and extend the life of mine, operations globally are increasingly expanding their cave footprints. At the Padcal Mine, a historical reliance on vertical extensions has recently transitioned into a strategic lateral expansion, driven by favourable metal prices, which has forced development into the highly stressed peripheral margins of the orebody.

2.1 Operations history

The Padcal Mine has a continuous operational history dating back to 1958. The operation transitioned from surface open pit extraction to a slusher-type block caving system utilising finger raises, ultimately evolving into a fully mechanised block caving operation in 1994. Historically, extraction has systematically advanced downwards through the mineralised footprint of the orebody, progressing from upper elevations to successive lower levels at 1050, 1020, 908, 798, and 782 m above sea level. More recently, favourable metal commodity prices have facilitated the conversion of peripheral mineral resources into economically viable ore reserves. This economic shift has driven a lateral expansion of the active cave footprint, specifically at the 798 production level. Therefore, extraction is expected to extend beyond the original mineralised orebody and into the meta-andesite host rock situated along the eastern, southern, and western fringes of the orebody with lower metal grades (Figure 1).

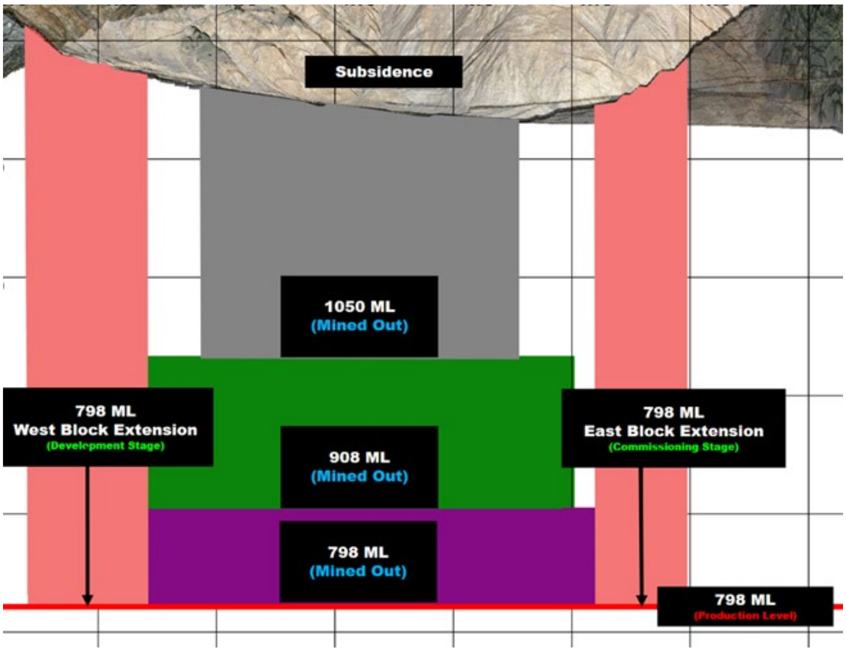


Figure 1 North-looking cross-section of the Padcal Mine, illustrating the historical progression of block cave expansion into deeper ore zones

2.2 The 798 mining level block extensions

The development of high-lift extensions within the 798 mining level presents distinct challenges depending on localised geotechnical conditions and existing infrastructure. Padcal initiated its footprint expansion in the southeast block, followed by the south and northeast blocks (Figure 2). The presence of pre-existing excavations – such as perimeter drifts, access ramps, and underground infrastructures – creates highly problematic geometries. Interactions between these existing drives and new development headings create wider combined excavation spans, compromise the structural integrity of both minor and major apexes, induce irregular undercut drift profiles, and result in critically thin pillars. Furthermore, managing the abutment stress under these ground conditions is essential to prevent damage to the extraction horizon and critical infrastructures located below the extension footprint, most notably the existing rehandling conveyor systems (Figure 3).

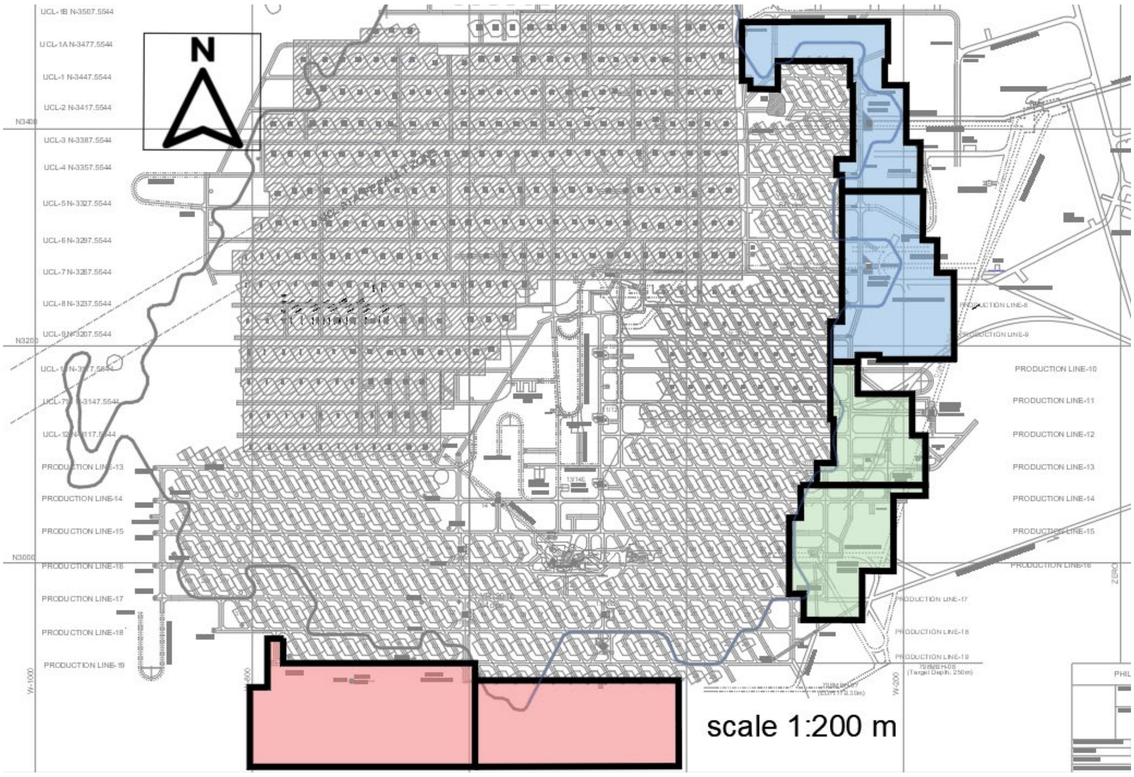


Figure 2 Plan view overlay of the 798 ML southeast (green), south (red), and northeast (blue) block expansions relative to the historical cave footprint

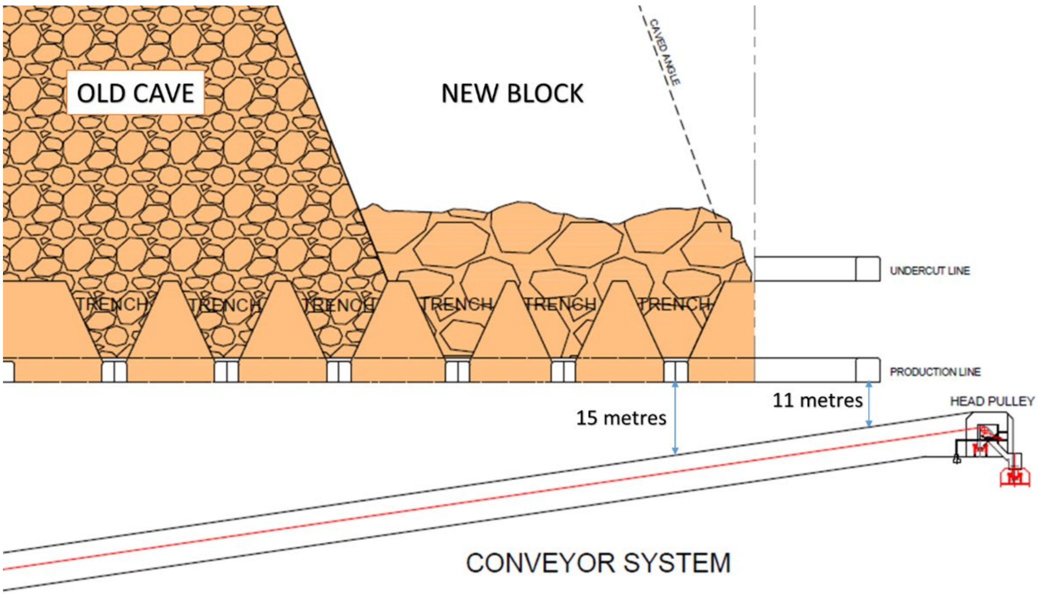


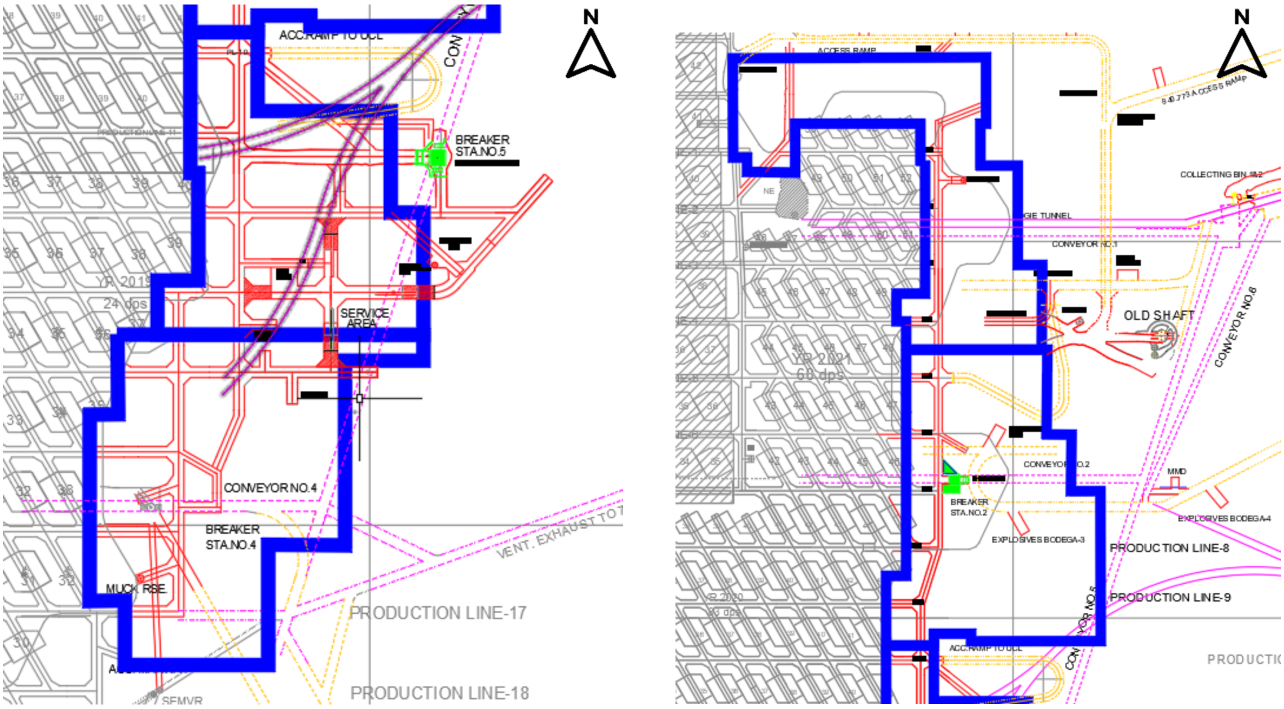
Figure 3 Cross-sectional schematic showing the proximity of the new extraction horizons to existing underlying rehandling conveyor systems

3 Challenges in cave expansions

At the Padcal Mine, introducing new development drives with existing infrastructures increases combined excavation spans, compromises pillar integrity, and accelerates ground deterioration. Concurrently, advancing into the high-stress abutments of adjacent caves triggers significant strain energy release, manifesting as rockburst seismicity at the margins (Esterhuizen 2018). Beyond structural challenges, exploiting these altered zones risks the ingress of saturated fines from the adjacent old cave, creating mudrush hazards that require strict draw control to prevent localised ratholing (Laubscher 2000; Butcher et al. 2005).

3.1 Underground infrastructures and pre-existing excavations

In mass mining, span interruption severely compromises the caveability of a block. Foundational caving principles (Brown 2003; Laubscher 2000) dictate that irregular undercut geometries and interrupted extraction horizons generate localised stress concentrations, which can arrest continuous cave propagation. At the 798 ML, the engineered layouts for the southeast and northeast block extensions directly intersect a primary access ramp, effectively severing the continuous cave connection between the 2 blocks. Furthermore, these extensions overprint existing perimeter drifts and underground maintenance shops (Figure 4).



(a) (b)

Figure 4 Plan view overlays detailing the geometric intersection of the projected cave expansion footprints (blue boundary) with critical pre-existing infrastructure, including permanent drives (red), access ramps (yellow), and underlying conveyor systems (magenta), at the (a) southeast block; and (b) northeast block

3.2 Seismic activity at cave margins

The primary challenge encountered during the development and early commissioning of the high-lift extensions was a significant and sudden increase in recurring rockburst seismicity (Table 1; Figures 5a–5d; Figure 6). Unlike typical cave propagation issues that occur during undercutting, these frequent seismic events were experienced prior to any undercutting activity, often occurring at the very onset of horizontal driving for block development. These seismic events demonstrated a distinct spatial pattern, with a high concentration of events located strictly at the cave margins and within high-stress abutment zones. This indicated a complex stress redistribution mechanism associated with the staged expansion of the cave.

Table 1 Summary of major rockbursts and seismic events at Padcal expansion drives (2022–2024)

Date	Mining level	Block	Affected pillars	Expelled rock (tonnes)	Recorded magnitude based on PHILVOLCS
3 July 2024	798	Northeast	PL 3 to PL 8 mainline and perimeters	204	2.6
3July 2024	773	Northeast	Conveyor 2,5, and 6, Bumolo ramp	104	2.6
22 May 2024	798	Northeast	PL 1B to PL 5	426	–
29 March 2024	798	Northeast	PL 2 to PL 7 mainline and perimeters	108	–
23 March 2024	798	Northeast	PL 1 to PL 4 mainline and perimeters	76	–
10 February 2024	798	Northeast	PL 6 to PL 8 mainline and perimeters	41	–
23 January 2024	798	Southeast	East perimeter 14 to 17	305	3.2
23 January 2024	814	Southeast	Undercut line (UCL) 13 to UCL 18	340	3.2
15 July 2022	798	Southeast	PL 13, 14, 15, 16, 17 mainline	566	–
15 July 2022	814	Southeast	814 UCL 15,16,18 east perimeter 1	102	–
7 April 2022	798	Southeast	PL 12 mainline	25	–
25 September 2021	798	Southeast	PL 12 and PL 13 mainline	21	–

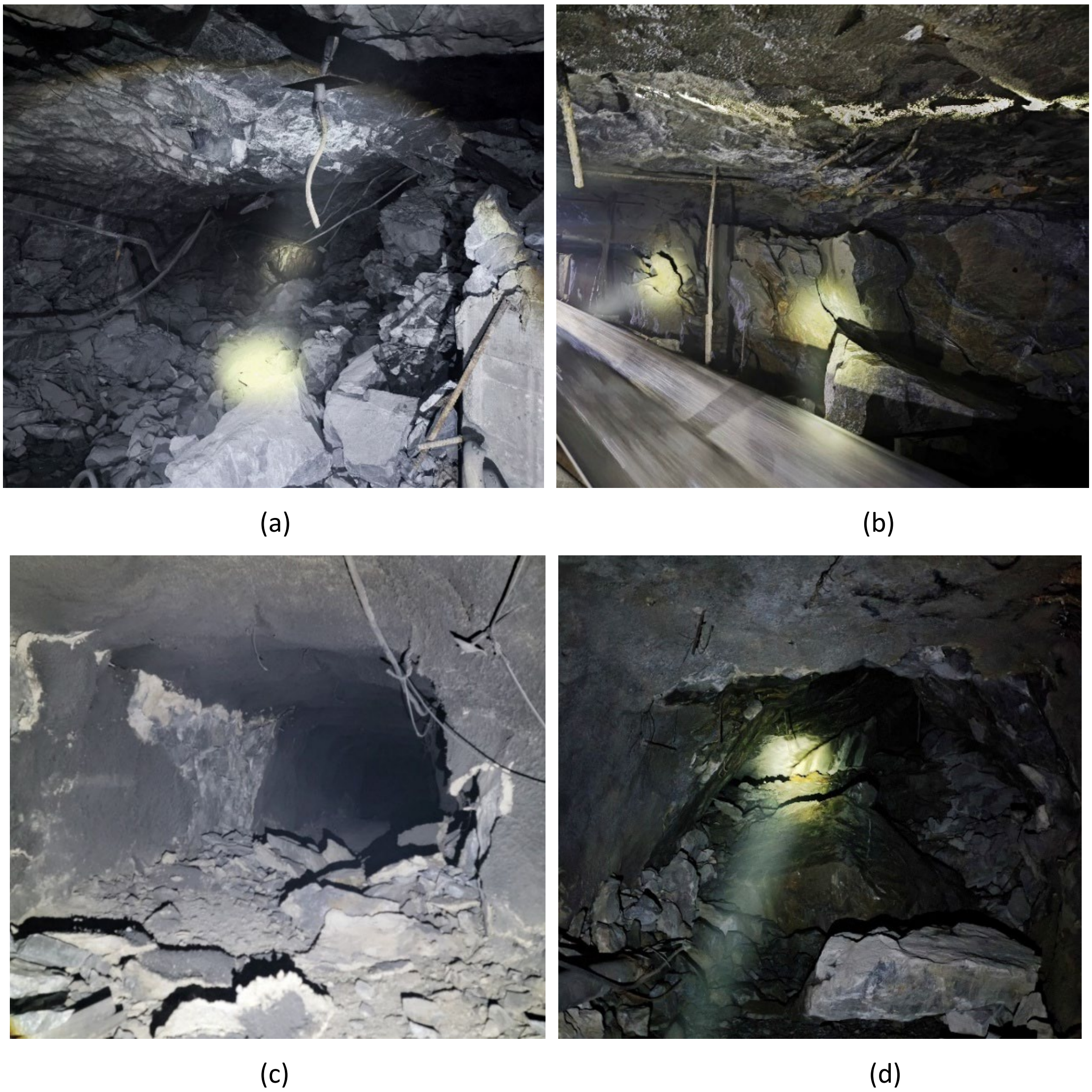


Figure 5 **Photographic evidence of seismicity-induced rock mass degradation across critical mine infrastructure. (a) New perimeter drives at northeast block; (b) Existing conveyor structures below northeast block; (c) Undercut level drifts at southeast block; (d) Pre-existing access ramps at northeast block**

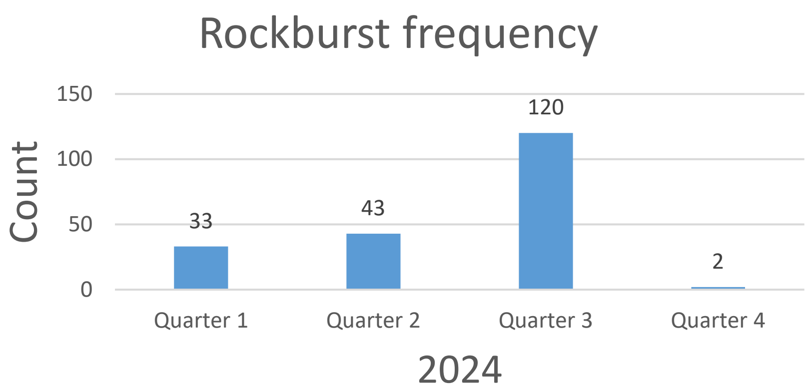


Figure 6 **Quarterly rockburst frequency across expansion blocks (2024) showing sudden Quarter 3 seismic escalation during early development and subsequent Quarter 4 stabilisation following development deferment**

3.3 Dilution entry, mudrush hazards, and draw control

A critical risk inherent to cave expansions is the lateral and vertical migration of waste material from the mature footprint into the active draw cones of newly commissioned blocks. This mechanism of premature dilution ingress across mature-to-new footprint boundaries has been extensively documented in other major industry expansions, notably during the mining of the Lift 2 North extension and the E48 extensions at Northparkes, where fine, remnant cave material rilled or migrated rapidly through the muck pile into adjacent new draw cones (Talu et al. 2010; Snyman & Webster 2022). See Figure 7 where the red overlay indicates the predicted lateral and vertical migration path of wet, fine backfill materials from the mature cave into the active draw cones of the newly commissioned block extension, a process accelerated by aggressive early extraction. At the Padcal operation, historical surface subsidence backfilling – originally implemented to mitigate mudrush occurrence into the depleting ore of drawpoints during the wet season – has introduced heavily saturated, fine brown materials into the old cave. The premature influx of these fines into the active extraction horizon is not merely a grade dilution issue; it constitutes a severe geotechnical hazard. The combination of active groundwater seepage and the infiltration of these fine materials creates conditions highly susceptible to localised liquefaction within the muck pile. This significantly elevates the risk of mudrushes at the active drawpoints, a hazard sharply exacerbated by the region's intense, high-precipitation climate. Operationally, the appearance of these distinct brown fines serves as a primary visual indicator of boundary dilution, which is initially flagged through routine ocular inspection and subsequently corroborated by grade sampling.

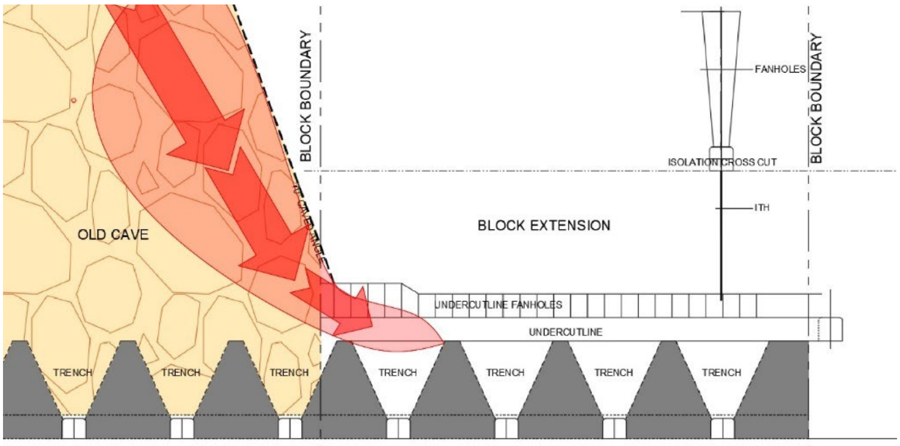


Figure 7 Cross-sectional schematic illustrating the risk of early dilution and mudrush hazards at the mature cave boundary (left) into the new cave extension (right)

4 Actions taken

Based on the monitoring data and field observations, mine management implemented a series of geotechnical interventions to mitigate the seismic risks, maximise ore extraction, and recover the headings.

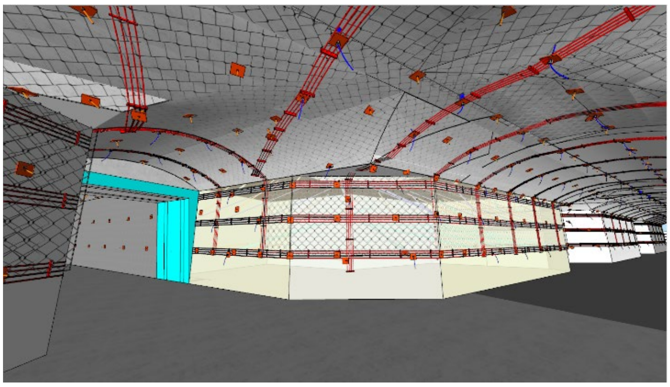
4.1 Enhanced active reinforcement systems and pillar reconstruction

To ensure the continuity of overall mine operations, severely damaged pillars and wide-span intersections within critical permanent infrastructure were rehabilitated immediately. Conversely, development activities within the highly stressed extraction horizon were deliberately suspended. In these active headings, rehabilitation and the installation of upgraded ground support were strategically deferred for several months to allow the localised rock mass to naturally stabilise and dissipate seismic strain energy.

4.1.1 Active support reinforcement

The mine mandated the installation of enhanced, dynamic reinforcement systems engineered to yield and absorb seismic energy while maintaining excavation profile integrity. Historically, standard extraction drive support – comprising conventional rockbolts, fibre shotcrete, and standard cable bolts – was sufficient for Padcal's operations. However, as established in rockburst support literature (e.g. Kaiser et al. 1996; Potvin et al. 2010), conventional static support systems are designed primarily to suspend gravity-driven rock wedges. They lack the deformation capacity required to survive the rapid kinetic energy release associated with strain bursts. When subjected to violent stress redistributions at the cave margins, rigid elements such as fully grouted rebar abruptly rupture, and plain shotcrete is forcefully ejected.

To survive this dynamic demand, the high-stress environment of the new expansion blocks necessitated a yielding support design. The upgraded ground support matrix integrates 30 t high-capacity cable bolts, high-tensile chain-link mesh, rigid welded mesh, and steel surface strapping (Figure 8). This combination allows the rock mass to safely dilate and bulk, dissipating seismic energy through the controlled elongation of the bolts rather than experiencing sudden failure. For severely damaged pillars requiring immediate rehabilitation, a heavy-duty reinforcement strategy is applied. This involves the installation of double-layered rigid welded mesh and surface strapping, anchored deeply into the rock mass by a combination of 2.1 m rockbolts and 6-m-long cable bolts, followed by a substantial application of shotcrete to consolidate the system. Furthermore, ground support upgrades were extended to critical infrastructure located below the extraction level, such as conveyor drives and lower accesses. These areas, which historically required minimal support, are now subjected to induced abutment stresses from the overlying expansion. To secure these excavations, a hybrid system of passive and active support was installed. In highly confined or critical intersections, heavy steel sets and timber cribbing were erected. For the majority of these underlying drives, the walls and pillars are now systematically wrapped with high-tensile mesh and fully pinned with dense rockbolt patterns to prevent strain-induced unravelling.



(a)

(b)

Figure 8 Implementation of the decoupled, yielding ground support matrix. (a) Engineered 3D schematic detailing the integration of high-capacity cable bolts, mesh, and surface strapping; (b) Actual field application in a highly stressed extraction heading prior to shotcreting

4.1.2 Pillar reconstruction and void management

The geometric intersection of new horizontal development drives with existing tunnels resulted in critically thin and highly irregular pillars. According to pillar strength principles (Lunder & Pakalnis 1997), a low width-to-height (W:H) ratio prevents the formation of a confined, elastic core. Without internal confinement, the brittle rock mass degrades rapidly under the high induced stresses of the cave boundary, leading to progressive pillar yielding. To restore regional stability, these compromised pillars required immediate reconstruction and reshaping. Initial rehabilitation efforts utilised rigid passive supports, such as the installation of heavy steel beams and the pouring of structural concrete walls, to artificially widen and confine the pillars. However, rock mechanics dictates that stiffer elements within a parallel system attract the highest stress loads. Because the rigid concrete lacked the tensile strength and yielding capacity to accommodate dynamic rock mass convergence, the majority of these walls sustained severe fracturing and damage during subsequent seismic events. This failure empirically highlighted the necessity of yielding support in burst-prone conditions, prompting a permanent transition away from rigid concrete structures toward the heavy-duty active support systems (double-meshing and cable bolting) detailed in Section 4.1.1. In addition to pillar reconstruction, large excavations interacting with the expansion footprint – such as old access ramps, perimeter drifts, and abandoned underground shops – required comprehensive void management. Foundational caving literature (Brown 2003) emphasises that unsupported spans and structural voids at the cave boundary create massive stress shadows and act as initiation points for uncontrolled unravelling. Leaving these voids open would severely compromise the caveability of the overlying rock mass and initiate major span failures. Consequently, these large excavations were systematically backfilled using coarse waste rock and low-grade concrete mixture. To ensure adequate regional stiffness and consolidation, low-grade concrete was poured into the waste rock matrix, effectively plugging the voids and homogenising the stress distribution across the expansion footprint.

4.2 Blasting deferment and re-entry protocols

To address the severe safety risks posed by sudden strain bursts, Padcal implemented strict administrative and operational controls, most notably the strategic deferment of blasting and the enforcement of re-entry protocols. Following the spike in violent seismicity in the northeast block, all development activities in that sector were immediately suspended. To maintain mine development targets, operations were transitioned to the south block, which, being situated in a virgin rock mass further from the historical cave boundary, exhibited a significantly lower and more manageable stress profile. The decision to defer mining in the highly active northeast block is deeply rooted in the geomechanical principles of time-dependent strain relaxation. As established in rockburst management literature (Kaiser et al. 1996; Beck & Brady 2002), highly stressed, brittle rock masses require sufficient time to dissipate stored strain energy following a major seismic event or rapid stress redistribution. Continuously advancing a development face into a yielding rock mass prevents the establishment of a stable equilibrium, inevitably leading to violent kinetic energy release. By enforcing a mandatory 6-month exclusion period with zero development activity, Padcal allowed the localised abutment stresses in the northeast block to naturally stabilise and micro-fracture at a controlled rate. Upon re-entry in early 2025, the accumulated burst materials were safely mucked out, and the heavily fractured outer shell of the tunnel and drawpoints was systematically scaled back to expose the intact, stress-relieved host rock beneath. Once a stable profile was achieved, intensive structural repairs and ground support upgrades were executed. To govern daily operations across all expansion zones, stringent re-entry protocols were institutionalised. Following any significant development blast, a mandatory exclusion window is now enforced. An authorised re-entry team composed of geotechnical personnel and senior supervisors must physically inspect the blasted block and adjacent levels prior to the resumption of development operations.

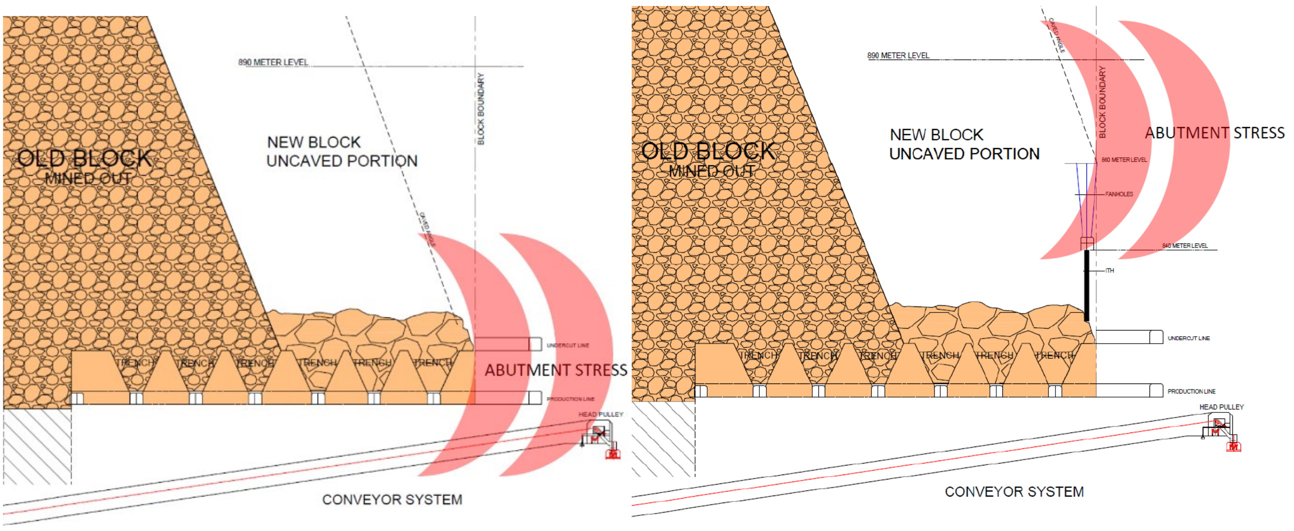
4.3 Isolation crosscuts and design adjustments

To proactively manage mining-induced stresses rather than relying exclusively on reactive ground support, Padcal implemented critical geometric modifications to the block boundary. Most notably, this involved the excavation of isolation crosscuts coupled with systematic 152 mm (6 in) down-the-hole (DTH) drilling

(Figures 7 and 9). These boundary boreholes, collared 26 m above the undercut level, are designed to intersect the terminal undercut fanholes. Following the primary undercutting sequence, these DTH holes are simultaneously blasted to establish a continuous fracture network and boundary slot along the block perimeter (Figure 9) following the excavation of the isolation crosscut and blasting of DTH boreholes.

By physically decoupling the active caving front from the surrounding rock mass, this engineered boundary slot functions as a geotechnical ‘circuit breaker’. As established by Andrieux & Hadjigeorgiou (2008), the creation of isolation slots forces principal stress trajectories to deflect around the artificial void, generating a destressed ‘shadow’ zone. This mechanism prevents the advancing cave abutment from transferring destructive stress transients onto critical permanent infrastructure, such as underlying conveyor networks and primary access ramps. Furthermore, the boundary slot artificially increases the effective hydraulic radius of the footprint from 35–38 m and provides a macro-scale plane of weakness, actively promoting the initial yielding and vertical propagation of the cave back.

Beyond boundary isolation, Padcal optimised its undercut sequencing to further manage abutment loading. Because the geometry and advance rate of the undercut face directly dictate the severity of induced stress (Laubscher 2000; Brown 2003), the engineering team integrated convergence monitoring into the production cycle. By dynamically tailoring the undercut advance based on the convergence response of the rock mass, the operation now caps progression at a strict limit of 6 drawbells per month, ensuring the cave propagates in a controlled, steady-state manner.

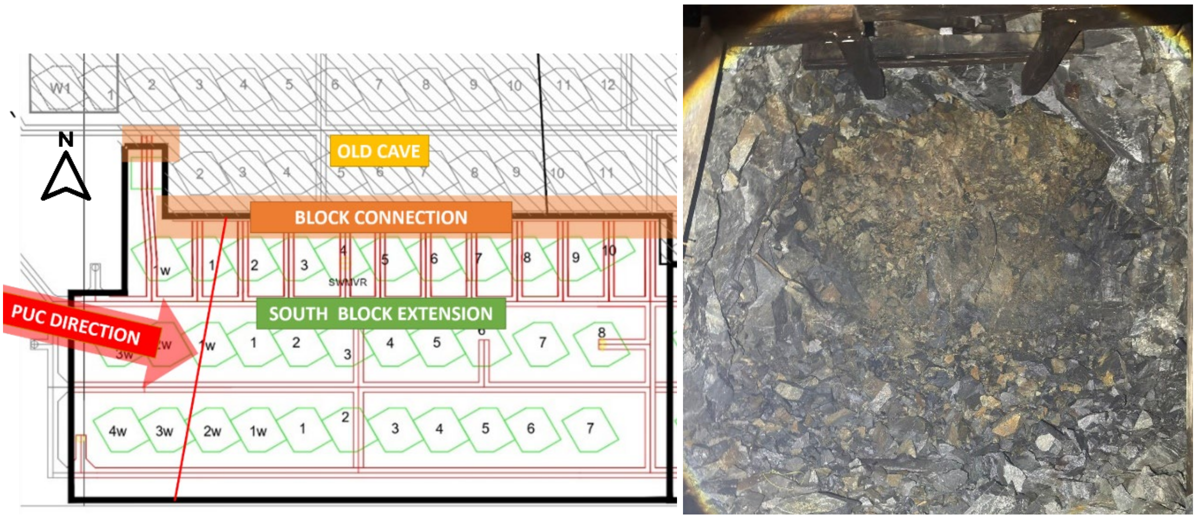


(a) (b)

Figure 9 Cross-sectional schematic of stress trajectories at the advancing cave abutment. (a) Direct, unimpeded stress transfer onto the extraction horizon without boundary isolation; (b) Deflection of principal stresses creating a destressed ‘shadow’ zone

4.4 Cave connectivity

A critical geomechanical requirement in cave expansions is the seamless integration of the new undercut horizon with the historical cave footprint. To ensure cave connectivity, development drives were extended to intersect the old cave boundary, and controlled blasting was utilised to deliberately loosen the boundary face. This methodology serves a dual purpose: it establishes the depleted cave as a massive volumetric free face for the initial undercut blasts, thereby ensuring high blast efficiency and immediate void creation. More importantly, connecting the undercuts mitigates the severe risk of forming a highly stressed remnant pillar between the historical and newly commissioned blocks. As documented in cave mining literature (Flores & Karzulovic 2002; Brown 2003), failing to physically connect the active and mature cave backs forces the unmined boundary column to act as a regional load-bearing pillar. This isolated geometry attracts immense abutment stresses, resulting in severe seismicity and the permanent sterilisation of ore. By poking through to the old workings, Padcal ensures a continuous, unified subsidence zone. While foundational literature suggests that advance undercutting can mitigate extraction level damage, the 798 Level extensions utilised a post-undercutting (PUC) strategy as the extraction horizon development had been fully completed prior to the onset of significant seismicity (Figure 10). The mine design focused on managing the inherent 'maximum front abutment stress' through strict retreat sequencing – advancing away from the historical boundary – and implementing the heavy-duty dynamic support systems necessitated by this method. To actively manage the high abutment stresses inherent to the PUC method, Padcal strategically sequences the undercut blast progression. Undercutting initiates directly at the cave connectivity zone (the historical boundary) and strictly advances away from the old workings, retreating into the virgin rock mass. This specific directional sequencing ensures that the massive induced stress wave is continuously pushed outward into the highly competent, unmined rock, rather than being trapped and concentrated between the advancing undercut face and the mined-out void.

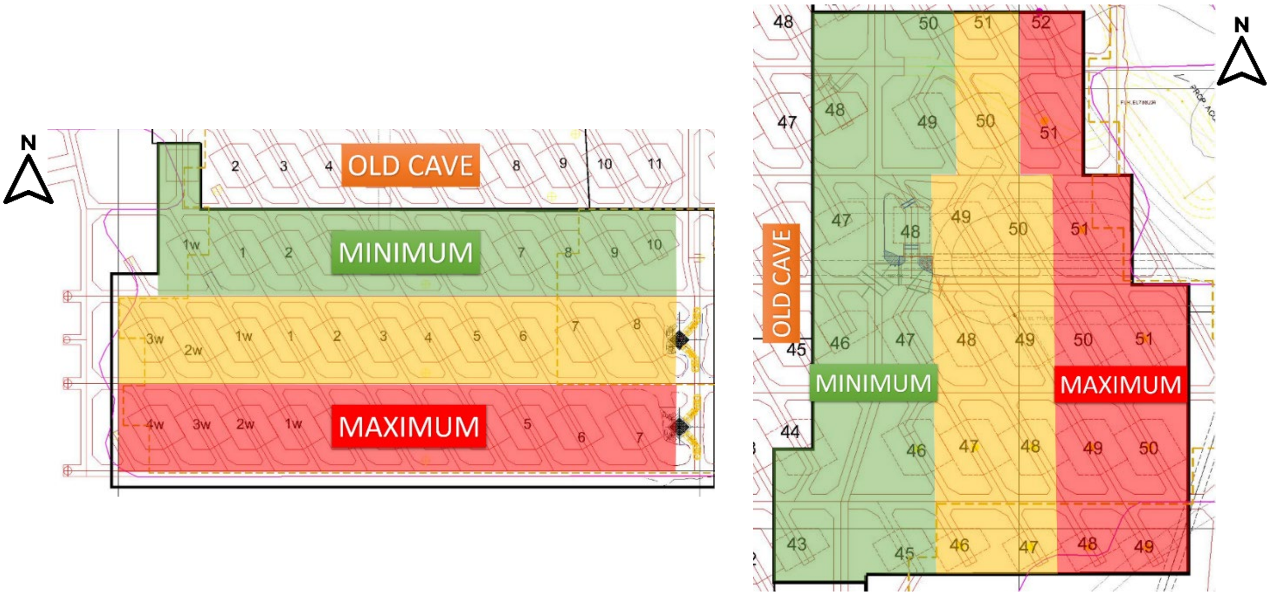


(a) (b)

Figure 10 Interface between the active caving front and the historic cave. (a) Engineered extraction design detailing the boundary connection sequence at south block; (b) Actual underground conditions observed at the breakthrough face

4.5 Strategic draw control and dilution management

Draw control directly dictates drawpoint longevity and overall reserve recovery. To prevent stress-induced infrastructure damage and mitigate early dilution, draw management practices must be dynamically tailored to the actual geomechanical conditions and specific production requirements of the caving block (Heslop 2000; Laubscher 2000). To rectify the early dilution experienced in the southeast block, Padcal adopted an adaptive draw strategy modelled after successful industry precedents, specifically the E26 Lift 1 North expansion at the Northparkes mine (Snyman & Webster 2022). When advancing a new cave adjacent to a depleted footprint, Northparkes successfully managed boundary dilution by deliberately skewing their draw profile. Rather than drawing evenly across the footprint, they initiated maximum extraction at the drawpoints situated furthest into the virgin rock mass and progressively tapered the extraction rates to a strict minimum as the drawpoints approached the historic cave connectivity zone. Applying this methodology to the commissioning of the south and northeast blocks, Padcal engineered a strict maximum-to-minimum stepped draw control strategy (Figure 11). In this profile, the active drawpoints furthest from the old cave boundary are assigned the highest extraction targets, while the boundary drawpoints are tightly constrained to maintain the muck pile at a high elevation.



(a) (b)

Figure 11 Strategic draw control profiles to specific operational domains. (a) Cave propagation in the newly commissioned south block; (b) Proposed draw strategy in the northeast block

5 Outcomes

The implementation of these integrated geotechnical strategies – specifically the strategic deferment of development, the excavation of isolation crosscuts, and the enforcement of a strict maximum-to-minimum draw profile – yielded quantifiable improvements in both rock mass stability and operational safety. Prior to these interventions, the expansion margins experienced severe and recurring seismicity, culminating in a 566 t expelled rock failure and successive 3.2 local magnitude strainbursts. Following the mandatory exclusion period and the installation of the upgraded yielding support matrix, the highly stressed northeast block was successfully rehabilitated and commissioned in March 2026. While the newly implemented ground support configuration is currently stable and intact under close monitoring, its ultimate long-term resilience against high-magnitude dynamic strainbursts remains subject to continuous empirical verification as caving matures. Furthermore, the transition to an adaptive draw strategy is actively mitigating the premature entry of wet fines, protecting the grade of the fresh ore columns and allowing for continuous, sustained caving in the south block extensions. Table 2 provides a comprehensive summary of the specific geomechanical challenges, engineered interventions, and operational outcomes across the 798 ML extensions, with supporting visual evidence detailed in Figures 12, 13, and 14. Figure 12 shows the frequency of rockbursts recorded from 2024–2026 after the deferment protocol while Figure 13 displays the chronological sequence of a specific pillar at the northeast block from its degradation after the seismicity, to rehabilitations, and actual status after abutment was introduced to it. Following strainburst damage on perimeter drives and the application of controls deferment and re-entry protocols, the affected pillars were scaled and stabilised with shotcrete and the installation of a high-capacity yielding support matrix (rigid mesh, surface strapping, cable bolts, and rockbolts). The successful stabilisation of the heading under maximum front abutment stress was validated by continuous convergence monitoring at the block (Figure 13). To systematically contextualise these operational parameters, Table 2 is organised into a matrix that aligns site-specific geomechanical hazards directly with their corresponding engineering and operational interventions. This is followed by a summary of the resulting structural and safety outcomes, providing a clear reference framework for the performance data gathered across the 798 ML extension sectors.

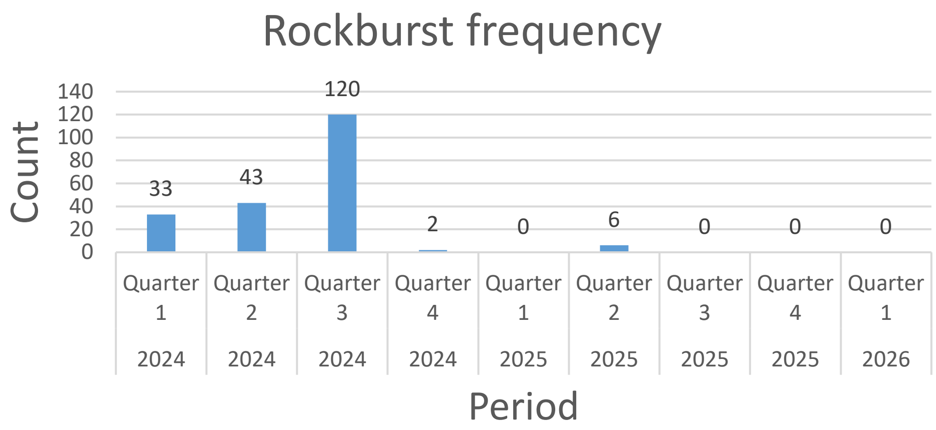
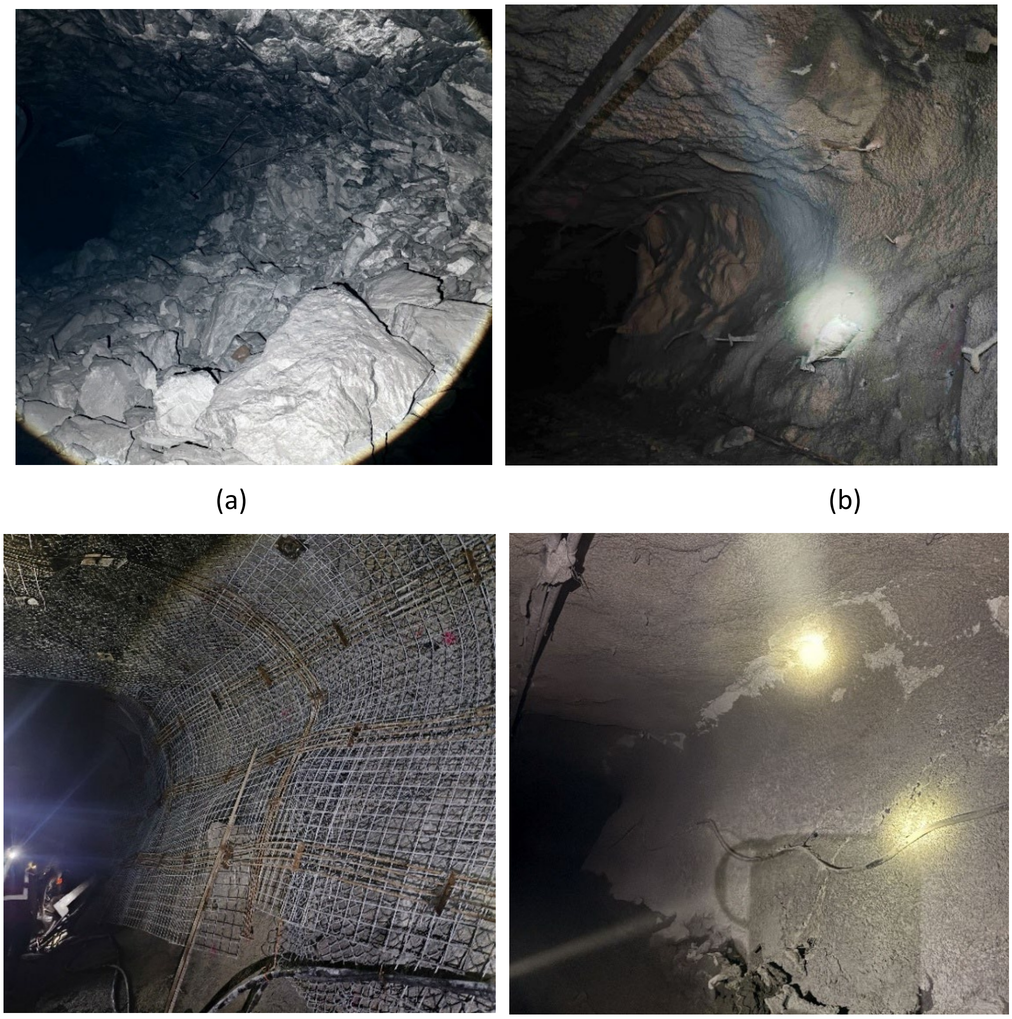


Figure 12 Recorded rockburst events (January 2024 to March 2026), showing sudden seismic escalation during early development and subsequent pillar stabilisation after deferment and re-entry protocols leading to successful block commissioning in March 2026



(a) (b)

(c) (d)

Figure 13 Chronological sequence of post-seismic rehabilitation and ground support application. (a) Initial strainburst damage on perimeter drives; (b) Scaling and application of a stabilising shotcrete layer; (c) Installation of a high-capacity yielding support matrix; (d) Successful stabilisation of the pillar post-commissioning

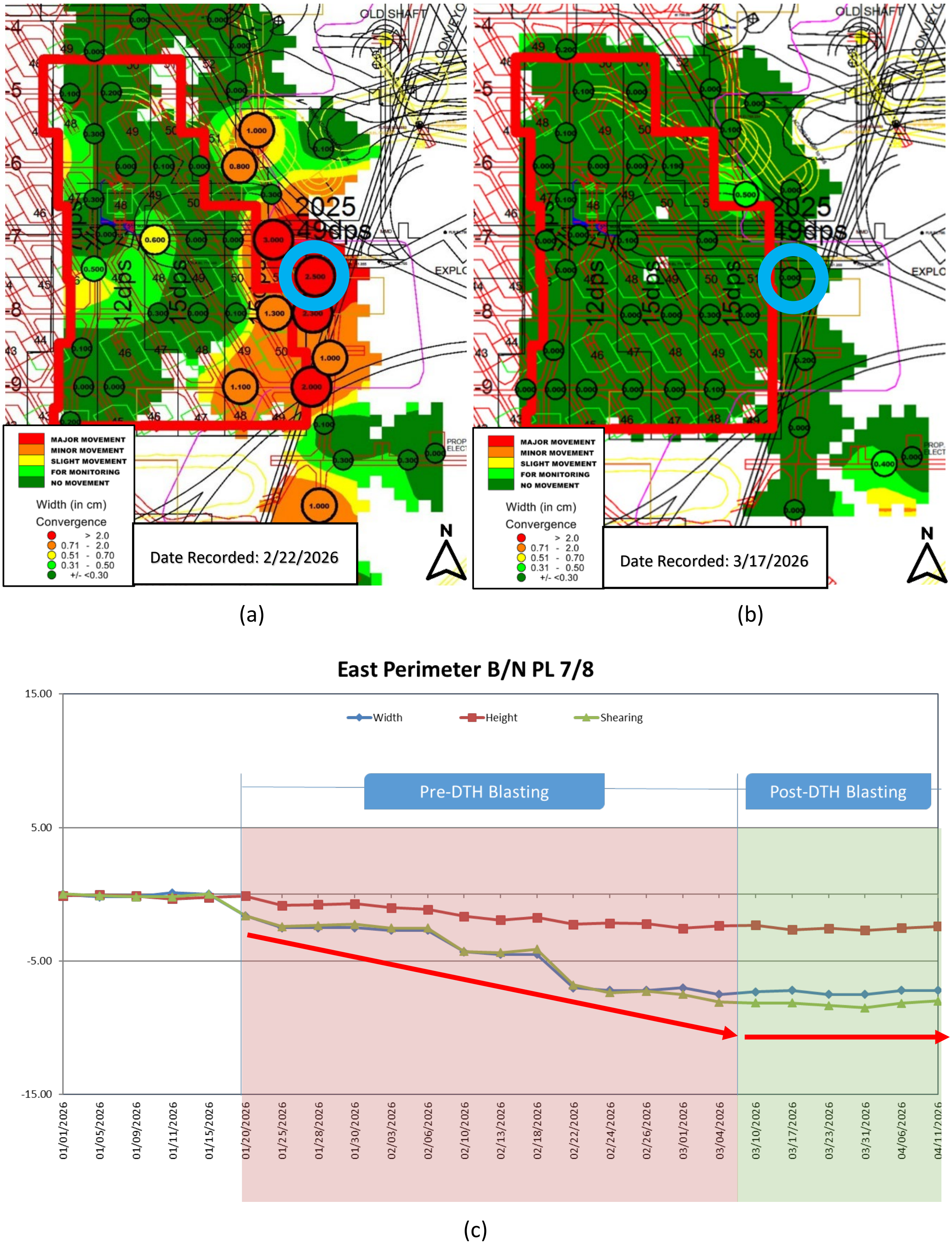


Figure 14 Pillar stability assessment via continuous convergence monitoring. (a) Severe ground convergence driven by advancing abutment stresses prior to intervention (20 January to 4 March 2026); (b) Immediate stabilisation of the east perimeter achieved post-down-the-hole blasting (10–31 March 2026); (c) Convergence rate per reading (centimetre) at the east perimeter monitoring station between production lines 7 and 8 (indicated by blue circles)

Table 2 Summary of primary geomechanical challenges, engineered interventions, and resulting operational outcomes in the 798 ML high-lift extensions

Geomechanical challenge	Pre-intervention condition	Engineered intervention	Quantifiable/operational outcome
Dynamic loading and seismicity	Severe, recurring strainbursts (up to 3.2 ML; >500 tons expelled rock) at active cave margins	Mandatory 6-month development deferment to allow for time-dependent strain relaxation	Near-complete cessation of major seismic events; successful block commissioning in March 2026 (Figure 12)
Ground support failure	Rigid concrete structures fracturing and abruptly failing under dynamic convergence	Implementation of a yielding matrix: 30 t cable bolts, high-tensile mesh, and steel surface strapping	Kinetic energy safely dissipated; minor bursts contained without catastrophic excavation profile failure (Figure 13)
Far-field stress transfer	Advancing cave abutment threatening vital, underlying rehandling conveyor systems	Excavation of boundary isolation crosscuts and simultaneous blasting of 152 mm down-the-hole boreholes	Principal stresses successfully deflected (destressed 'shadow' zone created); critical permanent infrastructure protected (Figure 14)
Early dilution and mudrush	Premature ingress of saturated, fine brown backfill into active draw cones	Implementation of an adaptive maximum-to-minimum stepped draw control strategy	Current draw strategy actively maintaining a high elevation boundary muck pile and protecting clean ore grade as extraction progresses

6 Conclusion

The extension of the Padcal Mine into deeper, peripheral zones via high-lift block caving highlights the critical balance required between aggressive production targets and dynamic geotechnical constraints. The successful commissioning of the 798 level expansion demonstrates that the severe operational hazards associated with mature boundaries – namely extreme abutment stresses, rockbursts, and early dilution – can be effectively managed. To reduce the inherent risks of connecting new production blocks to historically depleted caves, this case study establishes 3 core actionable lessons. First, boundary isolation crosscuts must be excavated early to function as geotechnical 'circuit breakers', shielding new development from destructive transferred stresses. Second, static ground support is insufficient at the fringes; dynamic-capable yielding support matrices must be deployed prior to undercutting to survive early-stage strain bursts. Finally, strict maximum-to-minimum draw control protocols are mandatory to ensure uniform stress redistribution and prevent the premature influx of mature cave fines. Ultimately, the Padcal experience proves that mining the highly stressed fringes of historical footprints is viable when engineered with a proactive, deep respect for mining-induced seismicity.

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Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Google Gemini to improve the language clarity, technical phrasing, and grammar of the manuscript. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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