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Using convergence monitoring and damage mapping to interpret ground behaviour in Padcal Mine block caving

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Abstract

Padcal Mine in the Philippines is one of the world's longest-operating block caves, with more than 6 decades of continuous caving and multiple cave expansions. As the cave footprint has deepened and widened, increasing abutment loading, evolving cave geometry and uneven draw have produced complex deformation patterns and recurring damage to critical underground infrastructures.

This paper presents a field-based approach for interpreting ground behaviour using convergence monitoring, systematic damage mapping, geological structural mapping and operational data from a mature block cave. Time-dependent convergence measurements from key haulage and production levels are analysed together with mapped damage, draw compliance and geological structures to identify whether ground movement is primarily stress-driven, draw-related or structure-controlled.

The results show that convergence monitoring and damage mapping provide a reliable basis for managing ground stability in a mature, high-stress block cave, with clear value for other long-life caving operations worldwide.

Keywords: *block caving, convergence monitoring, damage mapping, ground behaviour, abutment stress, draw control*

1 Introduction

Block caving is an efficient, large-scale underground mining method, but it fundamentally relies on the controlled management of induced stresses and rock mass deformation. As mature caving operations progress deeper and their footprints expand, the surrounding rock mass is subjected to complex, time-dependent stress redistributions (Brown 2007). In long-life operations like the Padcal Mine, where multiple cave expansions have occurred over six decades, interpreting these geomechanical responses is critical for maintaining the safety and stability of underground infrastructure (Figure 1).

The interaction between advancing undercuts, active draw columns and pre-existing geological structures creates dynamic load changes. Traditional numerical modelling provides baseline predictions; however, empirical field data is essential for calibrating these models and making real-time operational decisions (Laubscher 2000). This paper details a comprehensive, field-based methodology employing convergence monitoring and systematic damage mapping to interpret ground behaviour at Padcal. By correlating physical deformation data with operational extraction rates and geological mapping, ground movement can be categorised as stress-driven, draw-related or structurally controlled.

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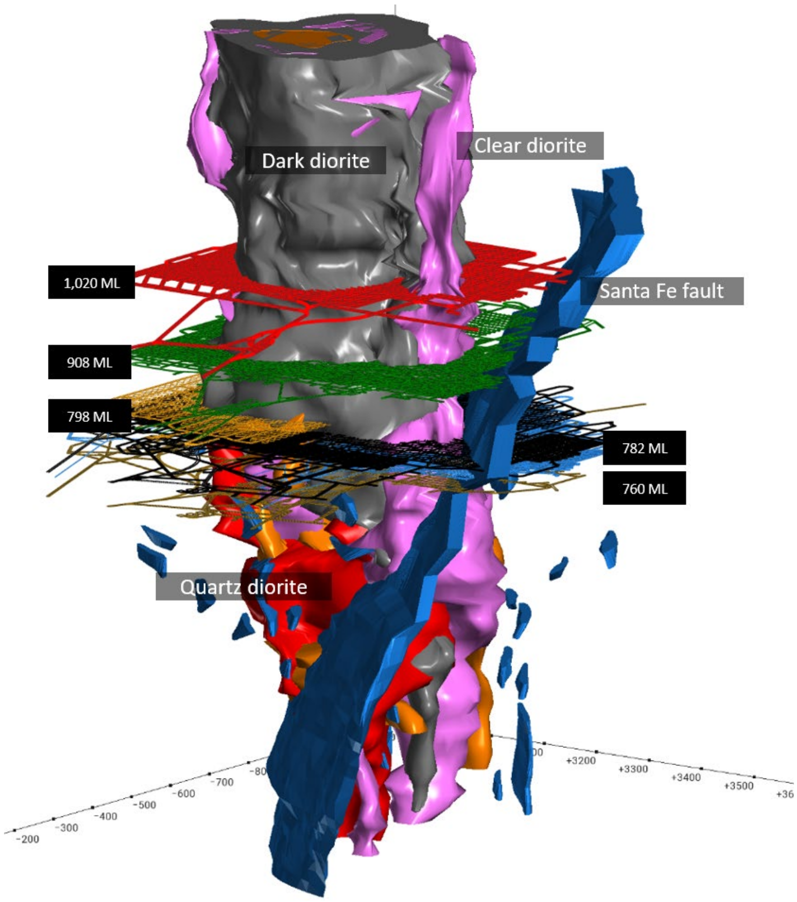


Figure 1 3D isometric geological model of the Santo Tomas II copper-gold porphyry deposit. The projection highlights the sub-vertical, pipe-like geometry of the orebody, which has been systematically extracted through successive lift elevations (1,050, 1,020, 908, 798 and 782 metre level). This multi-decade mining progression illustrates the cumulative spatial evolution of the cave footprint

2 Mine and geotechnical context of Padcal Mine

The Padcal Mine's geotechnical setting is defined by the interaction of a high-stress tectonic regime and a structurally controlled porphyry system. The competent Santo Tomas II orebody, hosted within dioritic and porphyritic lithologies, is intersected by major fault structures – most notably the Santa Fe Fault – which introduces localised zones of weak, squeezing ground. Under high k-ratio conditions at depth, these structural heterogeneities govern deformation behaviour and ground response. Accordingly, Padcal adopts a mining rock mass rating (MRMR)-based, condition-driven support strategy that is systematically adapted to both competent rock masses and structurally weakened domains.

2.1 Padcal geology

The Padcal Mine is a copper-gold operation owned and operated by Philex Mining Corporation and situated in the province of Benguet in the Northern Philippines. Padcal has been in continuous operation since 1958. Initially a surface mine, the open pit ceased operations in 1963, mandating a transition to underground extraction. The orebody Santo Tomas II was emplaced through four distinct episodes of intrusion and associated mineralisation into the Paleogene Zigzag-Pugo Formation along the steeply dipping Albian Fault. The primary lithologies include dark diorite, clear diorite and andesite porphyry. Deposition was locally controlled by the North, Middle and South Faults, which were the horsetail end of the northeast-trending major structure known as the Albian Fault (Figure 2).

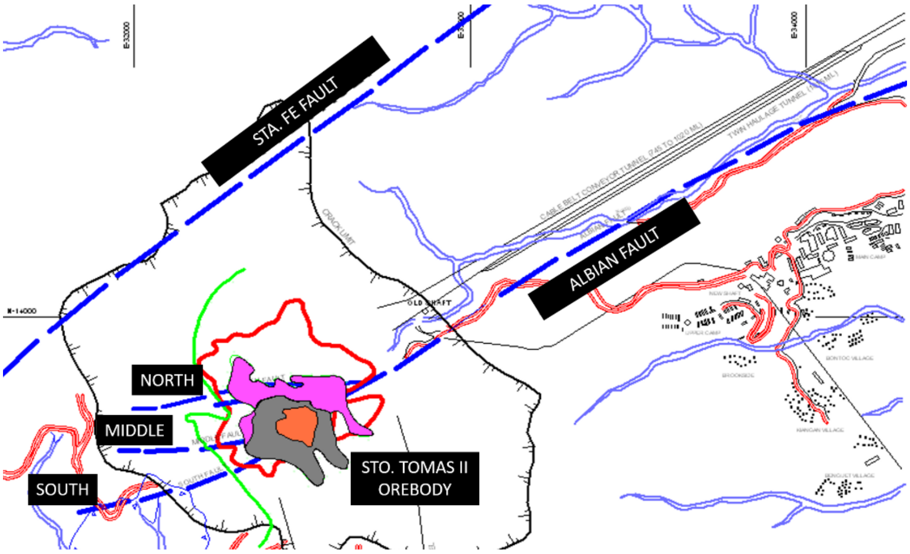


Figure 2 Geological model of the Santo Tomas II orebody, illustrating the central mineralised column comprising dark diorite (black), clear diorite (pink) and andesite porphyry (orange units intersected by major structural controls, including the Santa Fe and Albian Faults (blue dashed lines) and the North, Middle and South Fault splays

2.2 Rock mass competence and ground support system

The Santo Tomas II orebody is a massive, competent rock mass that poses distinct challenges for caveability and fragmentation. The fractures are tightly healed by secondary biotite, magnetite, chlorite, pyrite, gypsum and anhydrite. The Santa Fe Fault represents a zone of extreme geotechnical weakness. Its shear zone is approximately 50 m wide, characterised by 'Very poor' to 'Poor' rock mass classifications (Bieniawski 1989). Excavations traversing or situated near this fault at approximately the 25-metre zone are prone to squeezing conditions rather than brittle spalling. To manage these varying conditions, Padcal utilises two primary support classifications tailored to the local ground environment; however, these are adaptive, with specific reinforcements determined by onsite rock mechanics assessments. Tables 1 and 2 outline support systems based on Laubscher's Support Table Using MRMR (after Laubscher 1994).

Table 1 Support systems incorporated at Padcal

	Within Santa Fe Fault zone	Outside Santa Fe Fault zone
Rock mass rating	31–40	41–60
Initial support	Shotcrete (50 mm layer) initial rockbolts (grouted rebars)	Initial rockbolts (grouted rebars) Shotcrete (50 mm layer)
Final support	Cyclone wire mesh Final rockbolts (grouted rebars) Final shotcrete (varies) Concrete support (double matting 0.4 × 0.4 m rebar spacing) Structural steel sets	Welded mesh Tendon straps Final rockbolts (grouted rebars) Cable bolts Final shotcrete (50 mm layer) Concrete support (single matting 0.3 × 0.3 m rebar spacing)

Table 2 The relationship between rock mass rating (RMR) and the mining rock mass rating (MRMR) and recommended support systems

Support table using mining rock mass rating (MRMR) (after Laubscher 1994)										
MRMR	**Rock mass rating (RMR)**									
	1A	**1B**	**2A**	**2B**	**3A***	**3B***	**4A**	**4B**	**5A**	**5B**
	←Rock reinforcement – plastic deformation→									
1A										
1B										
2A										
2B	a	a								
3A	b	b	a	a						
3B	b	b	b	b	b	c				
4A	r	r	c	c	c	d	d			
4B*				d	**e**	**f**	f	c + l		
5A						f/p	h + f/p	h + f/l	h + f/l	
5B							h + f/p	f/p	t	t

* Philex

Support technique:

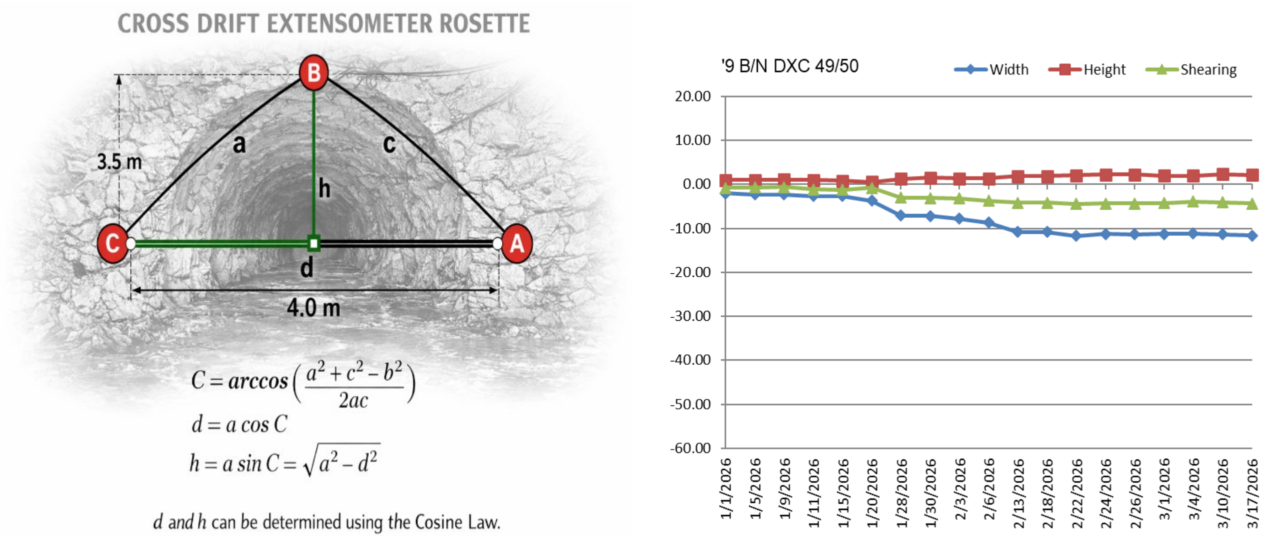
a	Local bolting at joint intersections	k	Rigid steel sets
b	Bolts at 1 m spacing	l	Massive concrete
c	‘b’ and straps and mesh if rock is finely jointed	m	‘k’ and concrete
d	‘b’ and mesh/steel-fibre-reinforced shotcrete bolts as lateral restraint	n	Structurally reinforced concrete
e	‘d’ and straps in contact with or shotcreted in	o	Yielding steel arches
f	‘e’ and cable bolts as reinforcing and lateral restraint	p	Yielding steel arches set in concrete or shotcrete
g	‘f’ and pinning	q	Fill
h	Spiling	r	Bolts and rope-laced mesh
i	Grouting	s	Rock replaced by stronger material
j	Timber	t	Development avoided if possible

3 Monitoring methodology and mapping

Throughout its operational history, the Padcal Mine has predominantly relied on pragmatic, site-specific geotechnical monitoring methodologies. Long-term empirical datasets demonstrate that conventional convergence monitoring has served as a highly reliable tool for analysing and interpreting complex ground behaviour during cave propagation. While manual convergence tracking is inherently labour-intensive and necessitates prolonged personnel exposure within active extraction horizons – a recognised challenge in continuous caving environments (Brady & Brown 2004) – strict adherence to operational safety protocols at Padcal has resulted in zero recorded incidents associated with these monitoring activities to date.

3.1 Convergence monitoring

Convergence monitoring is executed using cross-drift extensometer rosettes. As illustrated in Figure 3a, a standard 3.5 × 4m production drive is instrumented with anchor pins in the roof and walls, allowing for precise measurement vectors (wall-to-wall, diagonal). In wide underground infrastructures – such as large intersections or equipment service areas – only vertical stations are installed (roof-to-floor). The resulting data is illustrated in Figure 3b, which presents a line graph of the continuous convergence readings used to analyse ground movement and accurately assess the stability of the headings.

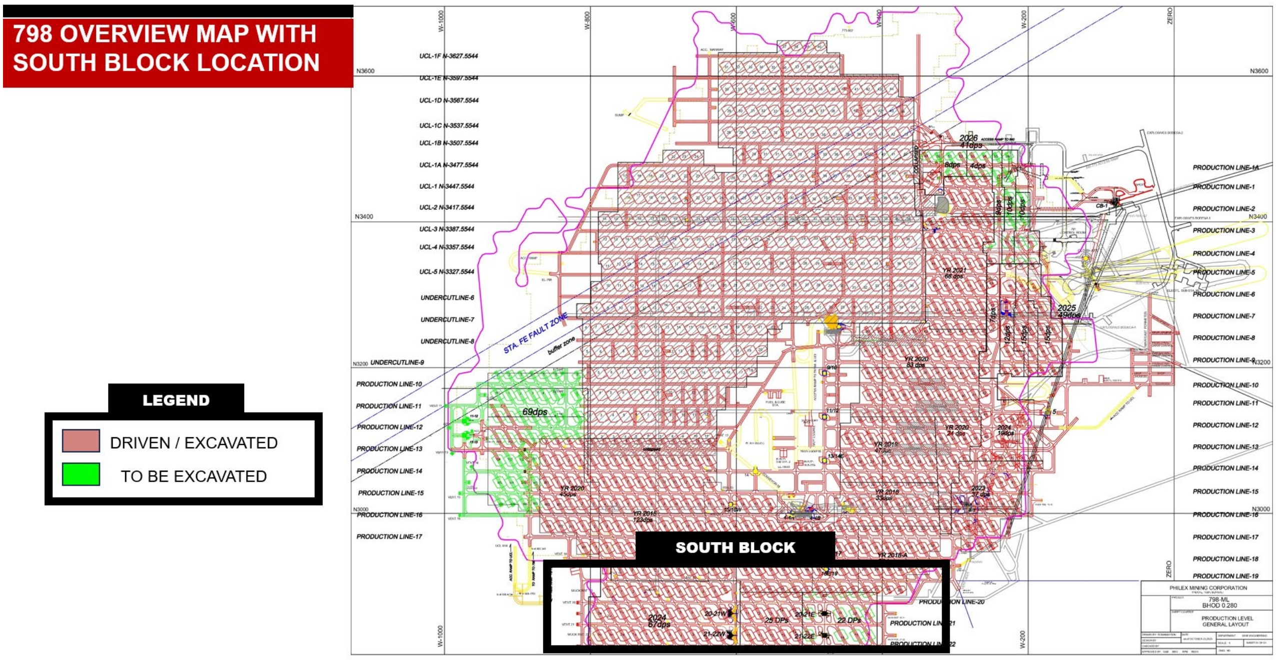


(a) (b)

Figure 3 Convergence monitoring at the Padcal Mine. (a) Schematic diagram of station installation detailing potential geomechanical interpretations of rock mass deformation; (b) Representative historical convergence data recorded at the active production level used in analysing width and height compression and shearing

3.2 Systematic damage mapping

Complementary to convergence monitoring is systematic damage mapping. Adopting the semi-quantitative classification scales established by Heal et al. (2006), damage at Padcal is categorised according to the specific criteria detailed in Table 3, with representative visual benchmarks illustrated in Figure 5. At Padcal Mine, systematic damage mapping provides empirical evidence of pillar deterioration, transforming actual inspections into a structured geotechnical database. As illustrated in Figure 4, this empirical repository facilitates the verification of observational reports and functions as a supporting diagnostic instrument for assessing the stability of all critical underground infrastructure.



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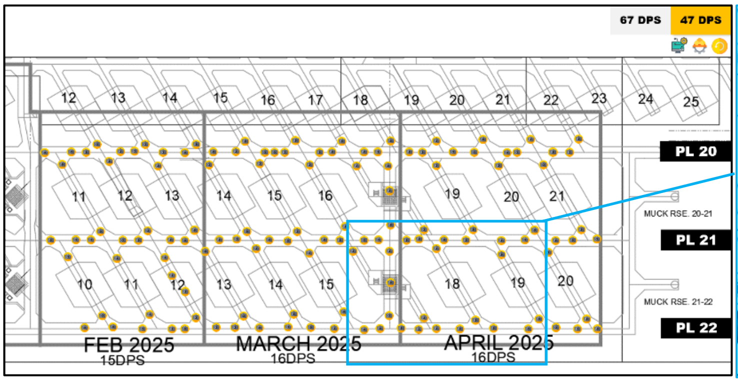

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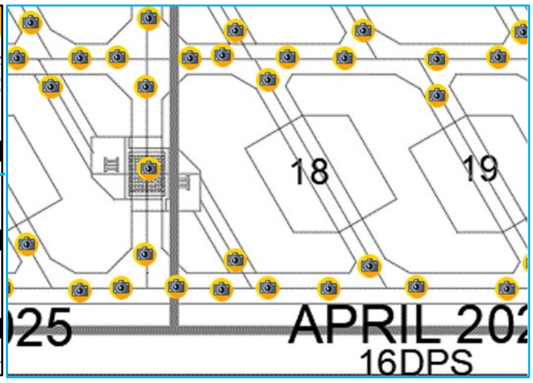

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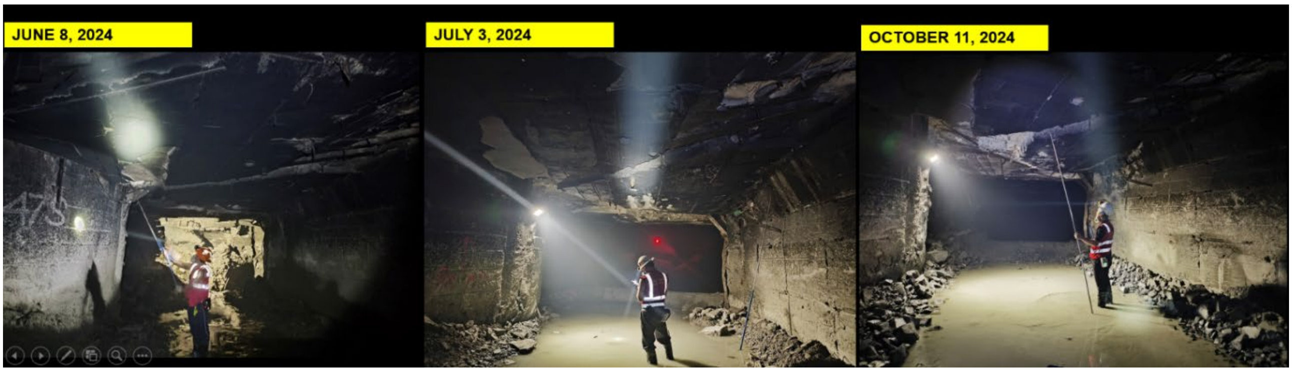


(d)

Figure 4 **The damage mapping is composed of (a) overview; (b) block map; (c) observation points; (d) chronological photographic records documenting the evolution of pillar deformation and support response**

Table 3 The Padcal 5-point damage mapping scale

Grade	Description of rock mass and support condition (rockburst damage scale after Heal et al. 2006)	Description of rock mass and support condition (Philex Padcal)
Grade 1	R1: No significant damage on rock mass, minor loose. No damage on supports	Minor shotcrete flaking and cracks present, no visible load on bolts or mesh
Grade 2	R2: Minor damage on rock mass, less than 1 tonne displaced. Support system is loaded, loose in mesh, plates deformed	Minor ground movement (1–2 cm). Spalling of shotcrete. Tightening of bolts and slight bagging of mesh
Grade 3	R3: 1–10 tonnes displaced. Some broken bolts	Major movement > 2 cm. Detachment of rock mass is evident. Significant shotcrete failure but active support elements still resist yielding and remain intact
Grade 4	R4: 10–100 tonnes displaced. Major damage to support system	Partial or isolated support failure. Broken bolts, tendons and mesh. Major damage to support system
Grade 5	R5: 100+ tonnes displaced. Complete failure of support system	Complete support failure, massive drift closure, impassable access

(a)

(b)

(c)

(d)

(e)

Figure 5 Visual benchmarks for the damage scale at Padcal Mine, illustrating characteristic rock mass responses and support deformation across varying intensities of pillar degradation as described in Table 3. (a) Cracking on shotcrete; (b) Spalling of shotcrete; (c) Yielding and maximum resistance of mesh and bolts; (d) Partial Support failure; (e) Complete support failure

3.3 Structural mapping as part of the geotechnical monitoring framework

Comprehensive structural mapping serves as the foundation of our geotechnical monitoring framework (Figure 6). Gathering this site-specific empirical data during drive development is an essential prerequisite for determining the most effective ground support strategies and ensuring the long-term stability of underground excavations (Hoek et al. 1995). This site-specific empirical data informs our initial support design; however, its true value is realised when integrated with observational data from convergence monitoring and routine damage mapping. While structural mapping provides the predictive framework for anticipated ground behaviour, convergence monitoring and damage mapping function as reactive tools, providing real-time verification of the rock mass response to mining-induced stress. Together, these datasets enable a dynamic, iterative approach to ground support management, ensuring that support strategies are systematically adapted to evolving site conditions.

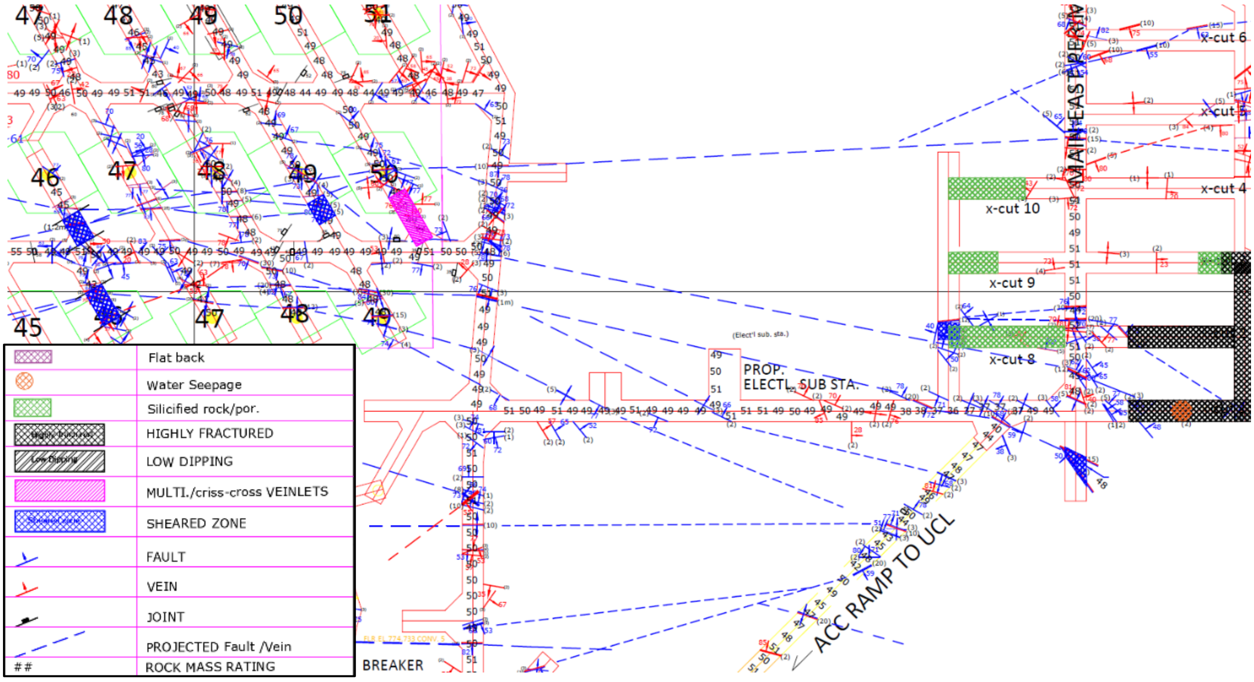


Figure 6 Detailed underground structural mapping capturing the spatial distribution of critical geological discontinuities, hydrogeological conditions and empirical rock mass ratings

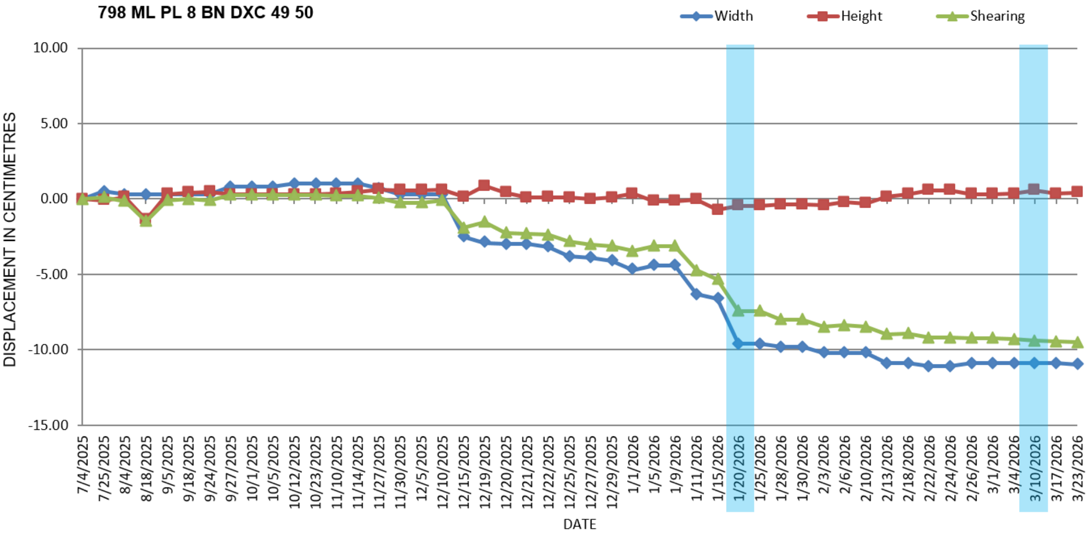
4 Application and analysis

The high-stress environment, combined with the observed structural heterogeneities, creates challenging ground conditions. Data from convergence monitoring and damage mapping consistently highlight areas where stress-induced deformation exceeds the capacity of standard support. Based on these monitoring data and field observations, mine management implemented a series of geotechnical interventions to stabilise the rock mass, maximise ore extraction and recover the affected headings.

4.1 Pillar instabilities during undercutting

During the undercutting phase, the vertical load previously carried by the blasted rock is transferred to the surrounding abutments. In deep, competent orebodies like Padcal's core diorite, this results in a high-magnitude, concentrated stress bulb ahead of the cave front.

Figure 7 demonstrates a time-based convergence graph from Padcal. Rapidly accelerating convergence rates typically indicate that the abutment stress has exceeded the intact rock mass strength, transitioning the pillar from an elastic state to a yielded, strain softening state. By continuously analysing this data, planners can alter the undercut advance rate. A faster advance rate can rapidly push the stress wave past critical infrastructure, quickly plunging the drives into the destressed stress shadow before time-dependent failure mechanisms can fully develop.



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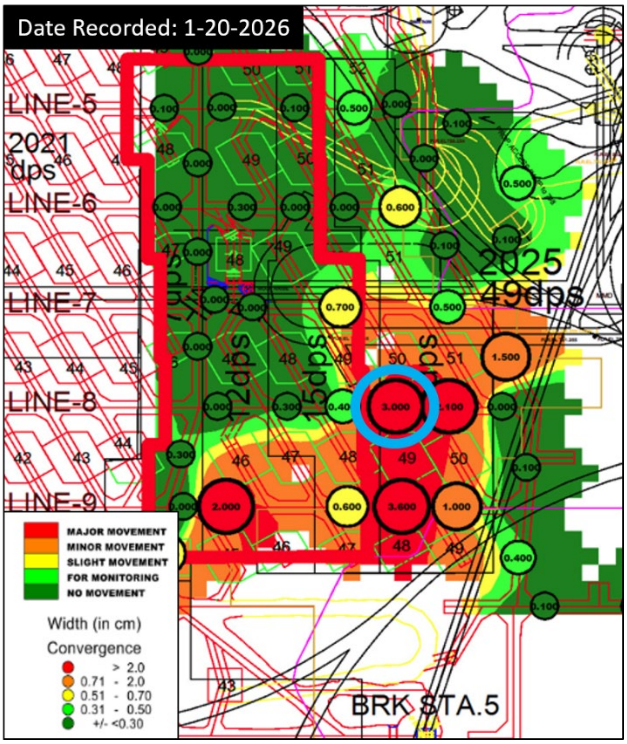

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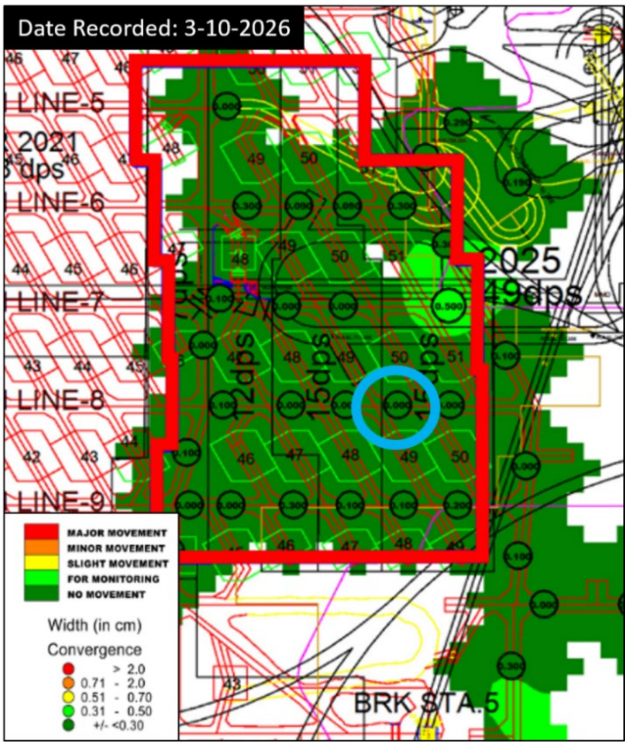

(c)

Figure 7 Geomechanical response to undercutting operations: (a) Measured displacement graph showing rapid stabilisation following the passage of the undercut front, with the blue shaded region indicating the monitoring interval (20 January to 10 March 2026); (b) and (c) Numerical convergence models illustrating simulated rock mass deformation in the northeast block at these respective dates. The blue circles in (b) and (c) identify the specific monitored pillars used as reference points for the convergence analysis

4.2 Production level monitoring and draw compliance

Once undercutting is complete, uneven draw significantly impacts ground stability. When extraction at certain drawpoints is significantly faster than adjacent ones, it creates an uneven caveback. This acts as an inverted topographical valley underground, routing massive vertical loads onto the 'peaks' (the un-drawn pillars) (Laubscher 2000). Furthermore, hang-ups and the subsequent secondary blasting required to clear them introduce severe dynamic shockwaves into already highly stressed pillars.

To directly correlate operational causes with geotechnical effects, Figure 8 provides a spatial map of draw compliance versus pillar convergence. The correlation confirms that poor draw compliance is directly proportional to pillar degradation, allowing extraction rates to be strictly dictated by geomechanical feedback.

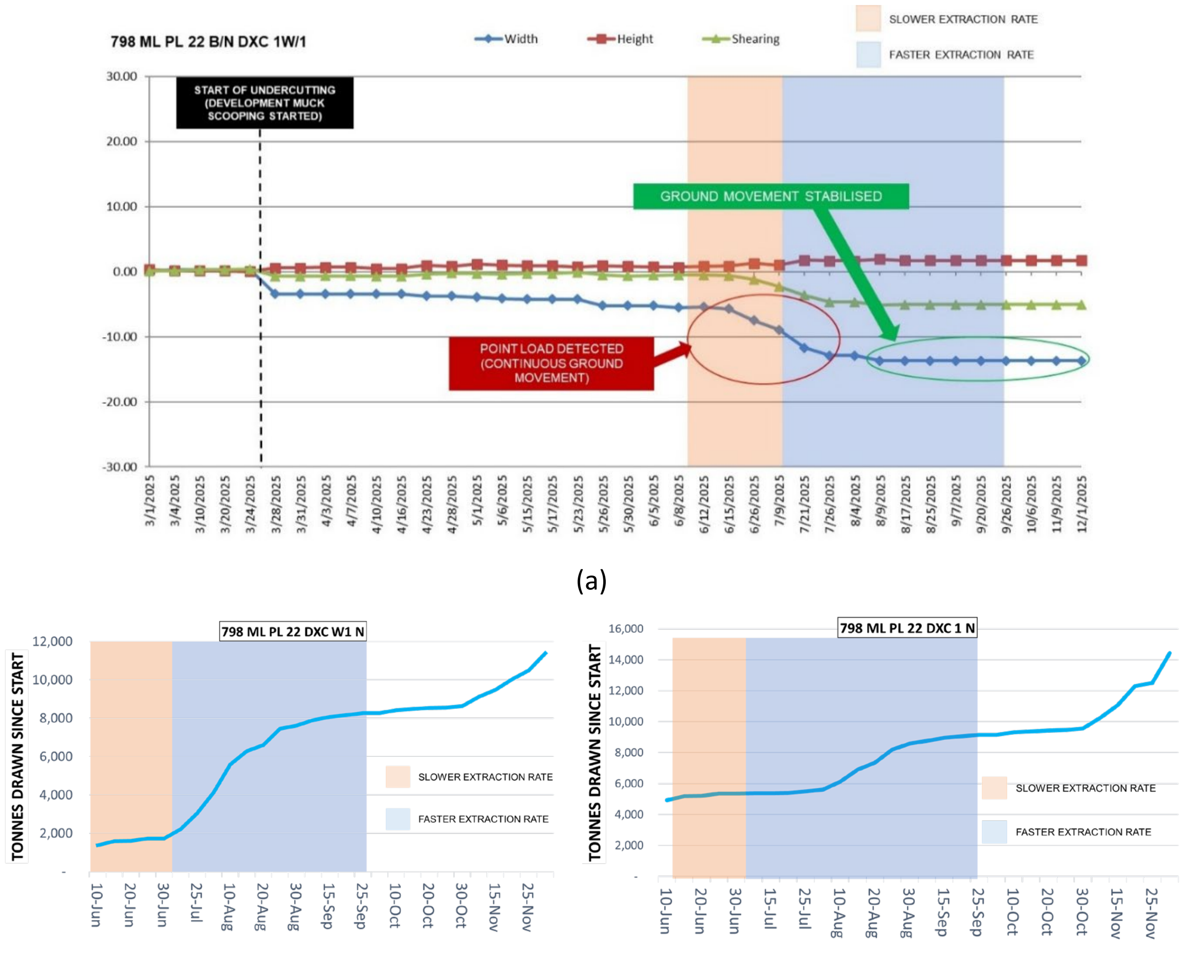

Figure 8 Correlation between extraction sequencing and excavation stability: (a) Time-series convergence data recorded between two drawpoints, highlighting a transient convergence spike from 26 June to 26 July 2025; subsequent stabilisation is attributed to the increased extraction of tonnage from two adjacent drawpoints as shown in (b) and (c), demonstrating the direct influence of draw compliance on mitigating induced pillar loading and controlling tunnel convergence

4.3 Squeezing ground and permanent structures

Within the incompetent domains of the Santa Fe Fault, the rock mass failure mechanism transitions from brittle spalling to severe, time-dependent squeezing. By correlating convergence monitoring data with structural mapping, significant and sustained ground deformation was quantified along the primary conveyor infrastructure. These critical, long-term excavations are situated directly within the fault's shear zone, subjecting them to continuous ground squeezing. Over time, the accumulated strain exceeds the yield capacity of the existing support system, manifesting as the gradual deformations illustrated in Figure 9. While the initial installation of passive ground reinforcement successfully decelerated the convergence rate, it proved insufficient to arrest the rock mass yield entirely, necessitating more yield-capable or rigid support interventions or a worst-case scenario of infrastructure abandonment.

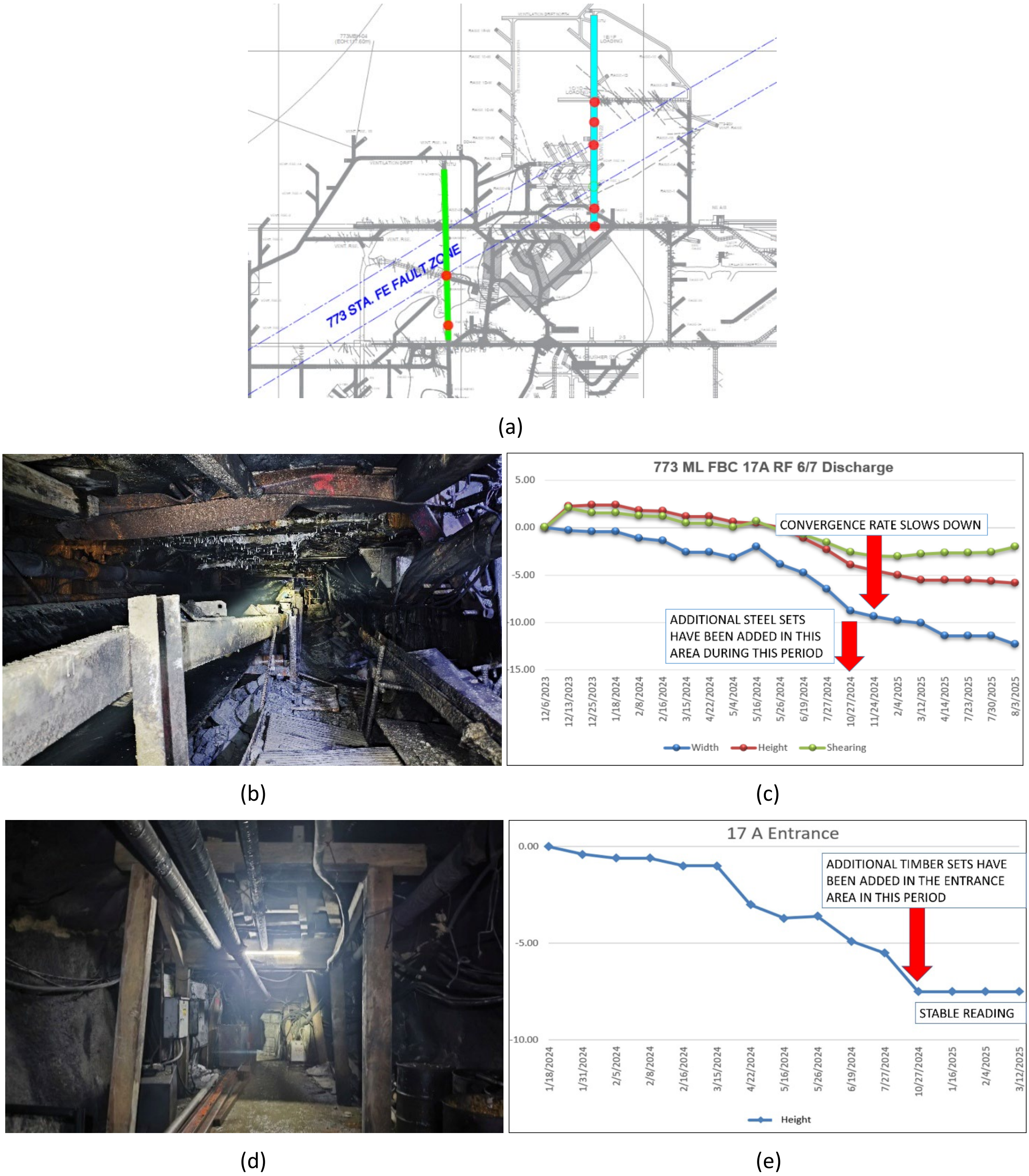

Figure 9 Geotechnical mapping and stability monitoring of the 773 metre level (ML) conveyor infrastructure: (a) Structural plan illustrating the alignment of feeder belt conveyors (FBC) 17A and 22 relative to the Santa Fe Fault boundary, with recorded high-magnitude ground movement highlighted in red; (b) and (c) Empirical damage mapping and longitudinal convergence data for FBC 17A, documenting persistent strain despite secondary reinforcement; (d) and (e) Structural response at the FBC 17A entrance drive, demonstrating successful stabilisation following the support interventions installed at the area

In line with these observations, the drifts and feeder belt conveyors (FBC) 17A and FBC 22 remain operational despite being located within the squeezing ground conditions of the Santa Fe Fault, primarily due to the continued economic benefit from the high-grade ore and tonnage of the old block at 782 ML. As convergence in this environment is unavoidable, preservation of these excavations is maintained only for as long as they are operationally viable.

5 Actions and mitigations

Through the integration of convergence data and damage mapping, Padcal implements mitigation strategies:

1. Undercut optimisation: the progression of undercutting generates a highly concentrated front of abutment stress. Continuous convergence monitoring allows engineers to modulate the speed and sequence of the undercut advance. If monitoring stations on the extraction level detect rapidly accelerating closure rates ahead of the cave front, it indicates that the abutment stress is dwelling on the footprint infrastructure for an excessive duration. By strategically increasing the undercut advance rate in these specific sectors, the operation can rapidly push the critical stress wave past the vulnerable excavations, effectively placing the underlying infrastructure into the destressed stress shadow before time-dependent rock mass failure can fully materialise.

2. Draw strategy adjustments: uneven draw profiles create dangerous inverted topographies within the caveback, routing severe point loads onto un-drawn pillars. When convergence monitoring correlates with differential draw – specifically when closure rates exceed 5 mm/day concurrent with grade 1 rock mass damage – immediate draw strategy adjustments are mandated. Geomechanical feedback dictates that extraction must be strictly halted in high-profile (over-drawn) areas. Simultaneously, ore is aggressively pulled from adjacent low-profile (under-drawn) zones. This targeted extraction flattens the caveback, dissipates the concentrated point loading and restores uniform stress distribution across the extraction horizon.

3. Ground support implementation: effective ground support design at Padcal is predicated on a triaxial diagnostic approach: identifying the fundamental drivers of instability, characterising the rock mass through historical structural maps and evaluating the localised geotechnical environment. This comprehensive assessment facilitates the selection of reinforcement strategies tailored to both ground demand and operational constraints. In development headings where equipment access is feasible, active reinforcement – including fibre-reinforced shotcrete, cable bolts, grouted rebars, straps and welded mesh – is deployed to provide immediate reinforcement and mobilise the rock mass's inherent strength. Conversely, in restricted or non-mechanised areas, passive support systems such as structural steel sets (I-beams), cast-in-place concrete liners, and timber sets are utilised to provide high-stiffness resistance against encroaching ground deformation. Historically, Padcal relied on rigid support systems in squeezing and poor ground conditions, which proved prone to brittle failure under high-convergence conditions. Consequently, the strategy shifted toward dynamic, yielding systems designed to accommodate sustained squeezing. Today, when monitoring detects accelerating convergence, severity-based rehabilitation protocols are immediately triggered. Early-stage movement (grade 2) prompts the installation of additional rockbolts and straps. In high-stress zones (grade 3), energy-absorbing systems like yielding mesh and bolts are deployed to allow controlled displacement without catastrophic failure. Under critical stress (grade 4), active support reinforcement utilising bolts, mesh and straps is combined with localised draw-rate adjustments to actively shed stress from the drift. Ultimately, this transition has significantly reduced rehabilitation frequency and enhanced extraction level safety.

4. Area Isolation: safety remains the paramount objective of the monitoring program. In extreme scenarios where convergence rates accelerate beyond 20 mm/day and the excavation concurrently exhibits grade 4 structural damage, the rock mass is considered to be in a state of imminent, uncontrollable unravelling. In these instances, the empirical data removes subjective bias from the

decision-making process. It provides mine management with the objective, quantifiable justification required to immediately suspend operations, safely barricade the affected zone and initiate a comprehensive revision of the mine plan to isolate the hazard.

6 Conclusion

Ground behaviour in deep, high-stress block caving cannot be managed on theory alone: it has to be read directly from the rock mass. At Padcal, the consistent use of convergence monitoring and damage mapping has allowed the operation to track how the ground actually responds, whether from advancing abutment stress, uneven draw or structurally weak zones transitioning into squeezing conditions.

The survival-driven extensions at Padcal Mine have introduced complex geotechnical challenges, with mining advancing into areas not originally planned and in close proximity to critical infrastructure. Thin pillars, multiple openings and high-stress conditions have resulted in severe ground responses, including rockbursts, where every operational decision carries risk.

Padcal's experience indicates that effective ground control can be maintained even without relying on sophisticated or high-cost monitoring platforms. Over the years, stability has been supported through careful observation and the consistent use of simple yet reliable tools. Despite these limitations, the team is able to capture, interpret and communicate ground responses to execute timely interventions. Specifically, routine convergence data triggers critical ground support rehabilitation and draw strategy adjustments. The effectiveness of the system does not come from the sophistication of the tools but from the consistency in how data is collected, validated and acted upon.

By anchoring decisions on trusted measurements rooted on gathered historical data rather than assumptions, the mine has enforced a dynamic, adaptive ground management strategy. By identifying early-stage convergence trends, the operation successfully intervenes before critical failure thresholds are breached. This approach has mitigated risks, prevented total block collapse and sustained operations. Padcal reinforces a fundamental principle for block caving worldwide: even straightforward, accessible methods, when applied with discipline and consistency, remain powerful tools for managing complex underground environments.

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References

Bieniawski, ZT 1989, *Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering*, John Wiley & Sons, Hoboken.

Brady, BHG & Brown, ET 2004, *Rock Mechanics for Underground Mining*, 3rd edn, Springer, Dordrecht.

Brown, ET 2007, *Block Caving Geomechanics: International Caving Study 1997–2004*, Julius Kruttschnitt Mineral Research Centre, Brisbane.

Heal, D, Potvin, Y & Hudyma, M 2006, 'Evaluating rockburst damage potential in underground mining', *Proceedings of the 41st U.S. Rock Mechanics Symposium (USRMS)*, American Rock Mechanics Association, Alexandria.

Hoek, E, Kaiser, PK & Bawden, WF 1995*, Support of Underground Excavations in Hard Rock*, A.A. Balkema, Rotterdam.

Laubscher, DH 1994, 'Cave mining – the state of the art', *Journal of the South African Institute of Mining and Metallurgy*, vol. 94, pp. 279–293

Laubscher, DH 2000, *A Practical Manual on Block Caving*, Julius Kruttschnitt Mineral Research Centre, Brisbane.