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Integrating mechanisms, monitoring and modelling for strainburst support design in deep cave mining

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Abstract

The increasing depth and scale of cave mining operations are exposing underground excavations to high-stress environments where brittle damage mechanisms dominate. Under these conditions, spalling and strainbursting govern the excavation response, yet current engineering approaches remain largely rooted in empirical methods developed for lower-stress and shear-dominated conditions. This paper presents a synthesis of recent advances that collectively establish a mechanistic and data-driven framework for strainburst hazard management and ground support design in deep cave mining. A data-driven methodology is first used to demonstrate that strainbursting is the dominant rockburst damage mechanism in a deep panel cave mine, with mining-induced stress redistribution identified as the primary trigger. A purpose-built geotechnical monitoring framework is then presented, integrating borehole imaging, convergence measurements and LiDAR scanning to quantify the depth of stress fracturing and bulking, providing early indicators of deformation demand. These monitoring observations are incorporated into deformation-based support design and preventive support maintenance strategies through empirical relationships that link fracture depth and displacement. Finally, bonded block modelling is used to explicitly simulate spalling and strainbursting, including both quasi-static and dynamic loading conditions, and to evaluate support system response under repeated loading. The integration of these components provides a comprehensive, field-validated framework that enables improved prediction, design and management of strainburst hazards in deep cave mining operations.

Keywords: *strainbursting, deep cave mining, deformation-based support design, preventive support maintenance, geotechnical monitoring, bonded block modelling*

1 Introduction

The mining industry is undergoing a fundamental shift toward deeper, larger-scale cave mining operations as near-surface resources are depleted and demand for critical minerals continues to grow. Block and panel caving are increasingly being adopted to extract massive, low-grade ore bodies at depth, with modern 'super cave' projects (Moss 2014) characterised by unprecedented footprint areas, extraction heights and depths now exceeding 1,000 m (Figure 1; Eberhardt et al. 2015). A step change in geotechnical complexity accompanies these trends, as deeper mining introduces higher in situ stresses, more massive and less jointed rock masses, and increasingly complex stress paths associated with undercutting, cave growth and abutment stresses. Under these conditions, excavation stability is no longer governed by shear-dominated mechanisms

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typical of shallower environments, but by stress-induced brittle damage processes involving spalling, strainbursting, and associated rock mass bulking (Kaiser et al. 2000; Diederichs et al. 2004). This transition presents significant challenges for design and operation, requiring a more rigorous understanding of brittle fracturing processes, post-peak behaviour and the resulting deformation demands placed on ground support systems to ensure safe and reliable excavation performance.

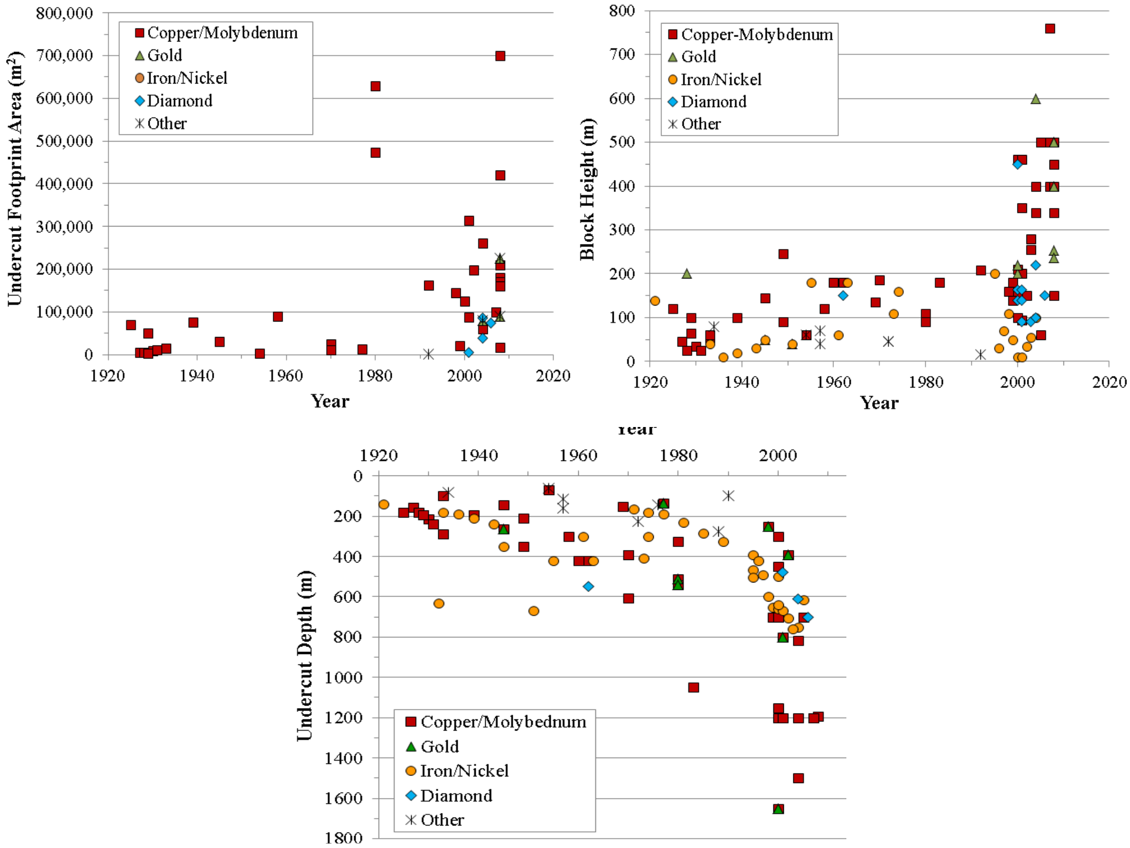


Figure 1 Block and panel cave footprint area, block height, and undercut depth trends, indicating a shift towards larger, deeper mines over the last 20 years. After Eberhardt et al. (2015) from data compiled by Woo et al. (2013)

In these conditions, excavation stability is governed by stress-induced brittle fracturing, which manifests as spalling and strainbursting. Spalling is a progressive excavation damage process involving the formation and detachment of rock slabs, whereas strainbursting involves the sudden and violent release of stored strain energy, leading to the rapid ejection of rock fragments (Ortlepp & Stacey 1994; Kaiser et al. 1996; Cai & Kaiser 2018; Roy et al. 2023). Rockbursts, broadly defined as sudden and energetic excavation damage, pose significant risks to personnel safety and infrastructure reliability (Hedley 1992; Heal 2010).

Despite extensive research, engineering approaches to rockburst hazard assessment remain limited. Many design methodologies are empirical and were developed for lower-stress environments, making them poorly suited to represent brittle damage processes and energy release mechanisms in deep cave mines. Furthermore, conventional monitoring approaches are typically reactive, focusing on displacement rather than the underlying processes that lead to damage.

This paper synthesises recent advances in data-driven analysis, monitoring, and numerical modelling developed by the International Caving Research Network (ICaRN) to establish an integrated framework for strainburst hazard management and ground support design. The work is grounded in observations and analyses from a deep panel cave mine and builds on recent advances in rockburst characterisation, monitoring design, deformation-based support design and bonded block modelling.

2 Getting the mechanism right

Rockbursts encompass a range of damage and trigger mechanisms, and accurate identification of the governing mechanism is essential for effective ground support design and hazard management (Cai & Kaiser 2018). A critical distinction exists between strainbursting, which involves local brittle fracturing and release of stored strain energy at the excavation boundary, and ground-motion-driven rockbursts, which are associated with dynamic loading from remote seismic events (Figure 2). Misidentification of these mechanisms can lead to inappropriate design strategies, particularly in deep mining environments where stress-driven processes dominate.

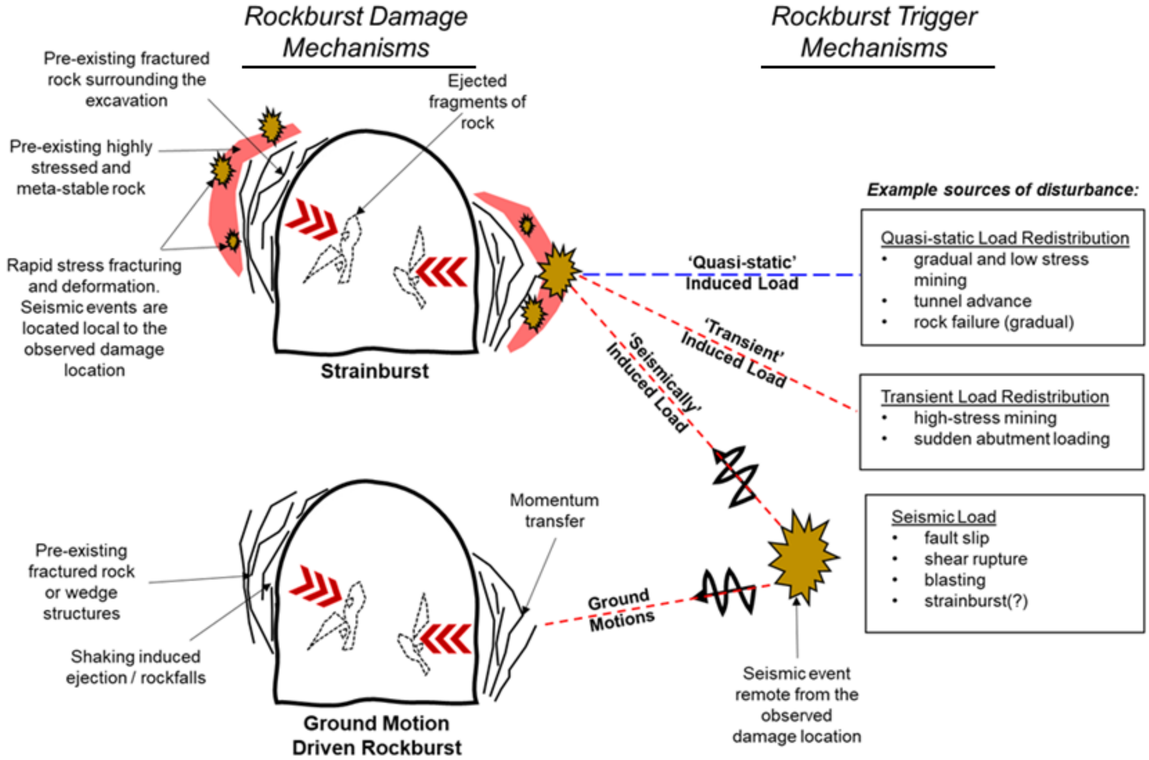


Figure 2 **Illustration of rockburst damage and trigger mechanisms occurring around a deep mine tunnel, contrasting strainbursting, where stress-fractured rock slabs are rapidly accelerated by the release of stored strain energy and accompanied by localised microseismicity, with ground-motion-driven rockbursts, where pre-existing fractured rock is mobilised by dynamic loading from remote seismic events. Modified after Roy et al. (2023)**

The deep mill level zone (DMLZ) panel cave mine, part of the Grasberg mining complex and operated by PT Freeport Indonesia (PTFI), provides a compelling case for establishing the governing mechanisms. The mine exploits the East Ertsberg Skarn System at approximately 1,400–1800 m depth, about 500 m beneath the deep ore zone mine (Figure 3a). Designed for a production rate of 80,000 t per day, Panel Block 1 (PB1) began undercutting in August 2015 following several years of development (Casten et al. 2016). The rock mass comprises strong, massive igneous and metamorphic units with sparse jointing, in which veining forms the dominant structural fabric (Hughes & Wiwoho 2005; Bewick et al. 2019; Figure 3b). High in situ stresses, characterised by a sub-horizontal maximum stress on the order of 60 MPa (Groccia et al. 2020), create conditions conducive to stress-driven brittle damage. The mining sequence, involving advanced development of extraction and undercut level drifts ahead of the cave front, progressively exposed extensive tunnel networks to increasing abutment stresses as the cave was expanded (Figures 3c and 3d). During the ramp-up period from August 2015 to March 2018, the mine experienced intermittent rockbursting that caused both localised and widespread damage to the extraction level, often associated with clusters of seismic activity within the cave abutments. These events elevated safety concerns, disrupted production and necessitated extensive rehabilitation and stress management (Simanjuntak et al. 2020).

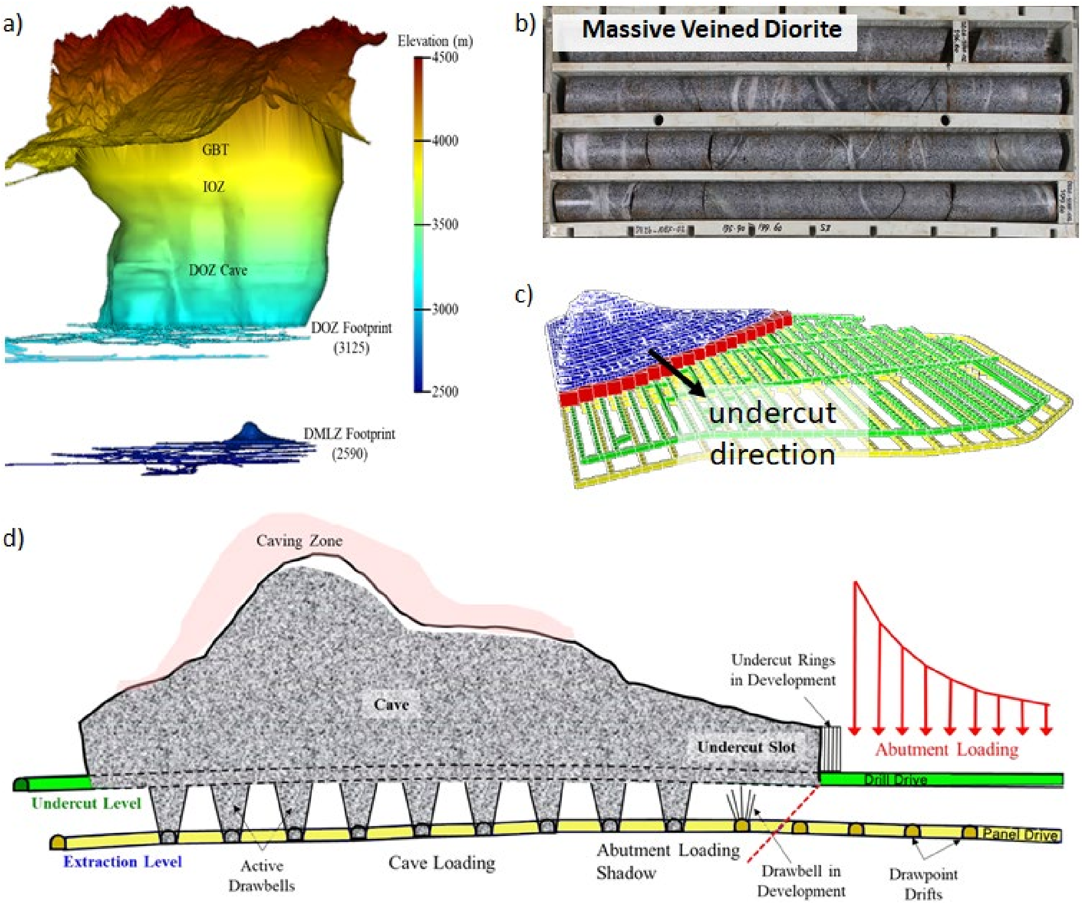


Figure 3 (a) View of the completed deep ore zone (DOZ) cave and early deep mill level zone (DMLZ) development in 2018; (b) Photo of core from massive veined diorite; (c) Cave shape model during cave initiation, showing undercut level (in green) and extraction level (in yellow); and (d) Schematic cross-section showing the cave abutment stress. Modified after Roy et al. (2023), McMillan et al. (2024) and Roy (2025)

The operational consequences of these events motivated the development of a data-driven methodology to identify the governing rockburst mechanisms. A rockburst characterisation database was compiled from field observations to capture localised damage and spatial-temporal clustering. Damage was systematically mapped using the rockburst damage index (RDI), adapted from the Kaiser et al. (1992) rockburst damage scale to record displaced rock volume and support condition along affected tunnels on a per-metre basis (Figure 4a). These data were aggregated through the rockburst cluster index (RCI), which quantifies cumulative severity and spatial extent (Figure 4b). This framework characterised 58 rockburst clusters across the footprint, independent of seismic monitoring limitations, and enabled the integration of geological, geometrical, operational and seismic datasets within a multivariate analysis framework (Roy et al. 2023).

Multiple independent lines of evidence from this analysis show that the observed damage was strainburst-driven rather than ground-motion-driven. Spatially, damage concentrated within the abutment stress zone ahead of the cave front and expanded with increasing cave hydraulic radius (Figure 4c), indicating strong control by stress redistribution rather than remote seismic loading. Temporally, each rockburst cluster coincided with short-duration flurries of seismicity localised within the footprint, with no evidence of large remote triggering events (Roy et al. 2023). Similar distributions of damage and seismic event counts relative to distance from the cave front (Figures 5a and 5c) suggest that seismicity was a direct expression of the damage process rather than an external driver. Furthermore, the weak correlation between RCI and the largest associated seismic event magnitudes (Figure 4c), compared to the strong correlation with total event counts, confirms that cumulative stress-fracture processes, rather than single dynamic impulses, governed damage severity.

a)

RDI	Rock Displaced (tonnes/m)	Visual Observations
1	None	Minor shotcrete cracking; rock mass retained by support.
2	0 to 0.1	Shotcrete cracking/spalling or local mesh tearing; small rock/shotcrete fragments loosened, ravelled or ejected.
3	0.1 to 2.5	Local support failure with exposed rock; stripped bolt plates; fragment ejection, but access remains possible.
4	2.5 to 10	Support failure with major loss of retention; 25–50% of drift filled by bulked or ejected rock; equipment access mostly impeded.
5	> 10	Support failure with large rock volumes bulked or ejected; drift more than half filled; no equipment access.

b)

RCI	RCI Range	Typical Operational Outcomes
I	< 100	Minor, localized mining disruption; local rehabilitation may be required.
II	100 to 200	Moderate disruption; local access loss and targeted rehabilitation required; possible localized production deviations, including uneven undercutting.
III	200 to 500	
IV	500 to 1000	
V	1000 to 5000	Hundreds of metres of damage; temporary mining suspension, local footprint access loss, major rehabilitation, and months of production disruption.
VI	> 5000	Thousands of metres of damage; temporary mining suspension, major footprint access loss, extensive rehabilitation, and many months of production disruption.

c)

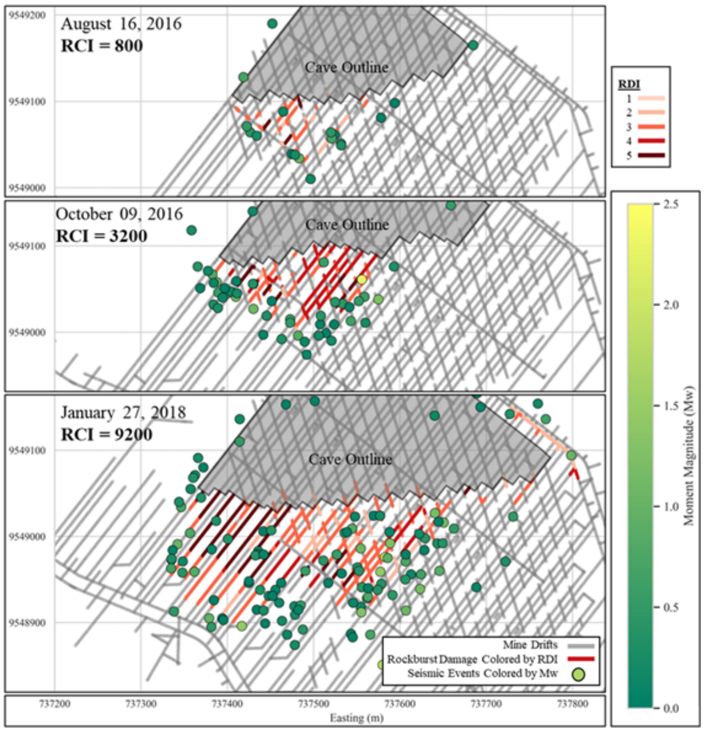
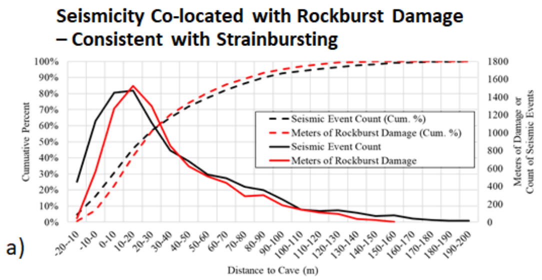


Figure 4 Descriptions of the (a) rockburst damage index (RDI) and (b) rockburst cluster index (RCI); (c) Examples of rockburst clusters and corresponding seismic events, shown as green circles coloured by moment magnitude, recorded during three stages of the Panel Block 1 (PB1) undercut advance, alongside mapped damage locations and RDI severity. Modified after Roy et al. (2023)



Trigger Analysis

Trigger	Count of Rockburst Clusters by RCI Class I	II	III	IV	V	VI	Total	Percent of Total
Blasting	17	12	8	2			39	67%
Mucking					4	1	5	9%
Unknown	11	2	1				14	24%
Total	28	14	9	2	4	1	58	
Percent of Total	48%	24%	16%	3%	7%	2%		

b)

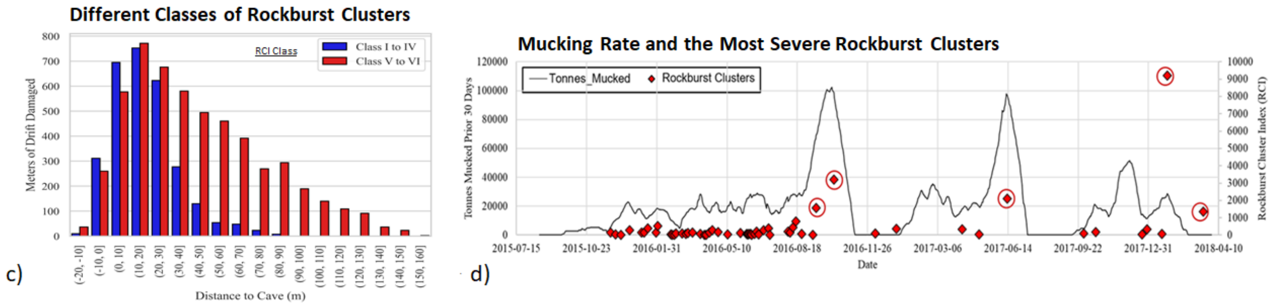


Figure 5 (a) Distributions of Panel Block 1 (PB1) rockburst damage and counts of seismic events with respect to distance from the cave for 58 rockburst clusters; (b) Count of rockburst clusters by identified trigger and rockburst cluster index (RCI) class, where blasting refers to load redistribution upon blasting; (c) Metres of rockburst damage grouped by RCI class and by distance to the cave; (d) Scatter plots showing rockburst clusters by RCI and tonnes mucked 30 days prior, with the 5 most damaging rockburst clusters circled in red and postulated to be related to periods of higher-than-average mucking activity. Modified after Roy et al. (2023)

Analysis of the triggering conditions (Figure 5b) shows that the majority of rockburst clusters were closely associated with mining-induced stress changes, with approximately 67 percent of events coinciding with blasting activities, particularly undercut ring blasting adjacent to the cave front (Roy et al. 2023). These events are not attributed to blast-induced dynamic loading, but rather to rapid stress redistribution within the abutments following excavation, typically expressed as short-duration flurries of seismicity localised within the footprint and spatially coincident with mapped damage. No large-magnitude remote seismic events were identified in association with the clusters, reinforcing that the damage was not driven by external ground motion or shakedown. The most severe clusters occurred during periods of elevated mucking rates (Figure 5d), which are interpreted to promote transient unloading of the cave back and elastic stress redistribution within the abutments, analogous to mechanisms described for deep tabular mining (Cook 1963; Salamon 1984). Collectively, the strong temporal association with mining-induced stress changes, the absence of remote seismic triggers, and the spatial overlap of both seismicity and damage to the abutment stress zone (Figures 5a and 5c, respectively) strongly indicate that rockbursting in the DMLZ was governed by localised energy accumulation, progressive stress fracturing and episodic release, providing evidence that strainbursting, rather than ground-motion-driven rockbursting, was the dominant damage mechanism.

3 Purpose-designed monitoring for deformation-based support design and preventive support maintenance

Stress-induced brittle rock damage around underground excavations initiates with the formation of extensional fractures once induced stresses exceed the damage initiation threshold (Eberhardt et al. 2016). The propagation of these stress fractures increases rock mass volume adjacent to the excavation, referred to as bulking (Kaiser et al. 1996), which governs the deformation demand imposed on ground support systems. This bulking is inherently directional, controlled by the kinematics of fracture opening and the geometric mismatch of fragmented rock (Rahjoo & Eberhardt 2021), rather than the uniform volumetric expansion commonly assumed in continuum-based design approaches. In the context of strainbursting, this behaviour is critical, as support systems must account not only for dynamic loading associated with rapid energy release but also for the accompanying bulking-driven deformation. In contrast to stoping operations, where rockburst support design typically focuses on dynamic capacity and systems are engineered to survive a single, localised strainburst event, deep cave mining presents a fundamentally different design challenge. The development of large hydraulic radii and extensive abutment stress zones leads to strainbursting that can affect hundreds of metres of excavations, with individual tunnels subjected to repeated loading as the cave advances. Consequently, support systems must be designed to withstand both dynamic loading and cumulative deformation demand, recognising that each strainburst progressively consumes available deformation capacity and necessitates timely intervention to preserve performance.

Deformation-based support design (DBSD) and preventive support maintenance (PSM) have emerged to address these limitations in conventional energy-based support design approaches. DBSD reframes support performance in terms of displacement demand and displacement capacity, recognising that support systems must be capable of sustaining bulking-driven deformation while maintaining their reinforcing, retaining, and holding functions (Kaiser & Moss 2021). Because displacement is both measurable and directly related to energy consumption, this framework provides a practical means to assess remaining support capacity and manage excavation performance over time (Di Ciolli et al. 2022). In practice, this enables support design to be treated as an evolving problem, with PSM implemented when measured displacement exceeds available capacity, rather than in response to visible damage or loss of serviceability. As emphasised by Moss & Kaiser (2022), this approach is most effective when embedded within mine-scale ground control systems using trigger-action-response strategies. At the DMLZ, these concepts were operationalised through the ground support scoping tool (GSST), as described in Di Ciolli et al. (2022), where the demand on the ground support is assessed based on expected brittle damage behaviour, including stress fracturing depth, bulking response, and strainburst potential, and compared against support capacity to guide intervention.

The application of this framework required reliable field-based measures of both stress fracturing and deformation, motivating the use of the extensive monitoring dataset collected during the PB1 ramp-up. McMillan et al. (2024) demonstrated that integrating borehole camera surveys and multipoint extensometers with convergence measurements and LiDAR scanning provides a more complete characterisation of rock mass response (Figure 6). Their analyses showed that the depth of stress-induced fracturing increases progressively as the undercut approaches, while corresponding deformation, expressed as bulking, remains partially constrained by installed support until a critical threshold is reached. As a result, direct measures of fracture depth provide an earlier and more sensitive indicator of increasing support demand than displacement measurements alone. Furthermore, they showed that while convergence data are useful for tracking temporal trends, they can underestimate the magnitude and variability of bulking due to their discrete nature. In contrast, LiDAR scanning captures the full excavation surface and better resolves spatial patterns of deformation, including localised and asymmetric responses.

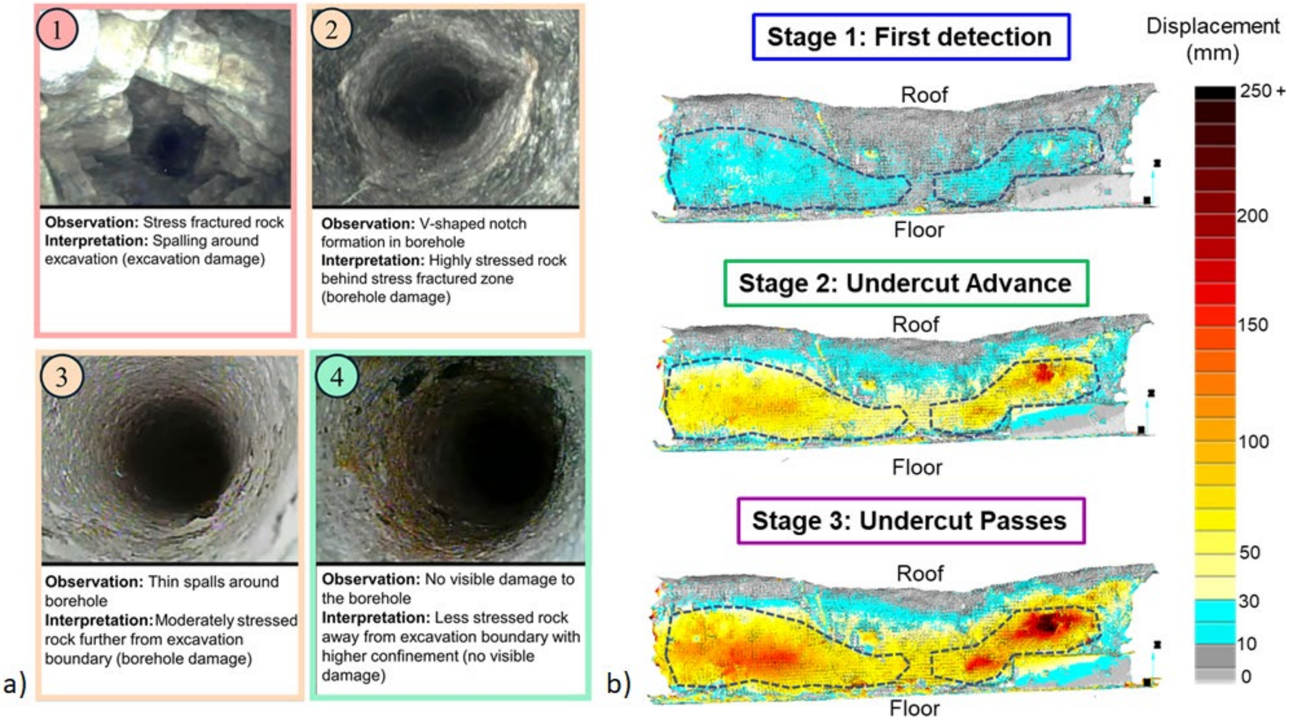


Figure 6 (a) Decrease in stress-induced damage with increasing distance from an extraction level panel drive wall, as observed in borehole camera imaging, showing a transition from severe stress fracturing near the excavation boundary to visible spalling in the monitoring borehole as an indicator of moderate damage, and ultimately to intact rock with no observable damage at greater distances; (b) LiDAR scans of a panel drive wall at three stages relative to the advancing undercut, showing the spatial accumulation and evolution of bulking along the supported excavation boundary, with the dotted line delineating the initial zone of detectable deformation. Modified after Roy et al. (2023) and McMillan et al. (2024)

Building on these findings, Primadiansyah et al. (2026) developed a purpose-designed monitoring system that PTFI deployed in Panel Block 2 (PB2) of the DMLZ. The setup integrated complementary, co-located measurements to capture stress fracturing and bulking (Figure 7), enabling a more rigorous and direct quantification of their relationship. The monitoring framework was integrated with the DBSD workflow implemented in the GSST, allowing excavation demand to be evaluated under both static conditions, defined by stress fracturing depth, bulking factor, and displacement demand, shakedown and dynamic conditions associated with strainburst potential. In this way, the monitoring system was designed not only to characterise rock mass response but also to generate the key parameters required for design calibration, support performance assessment and PSM scheduling.

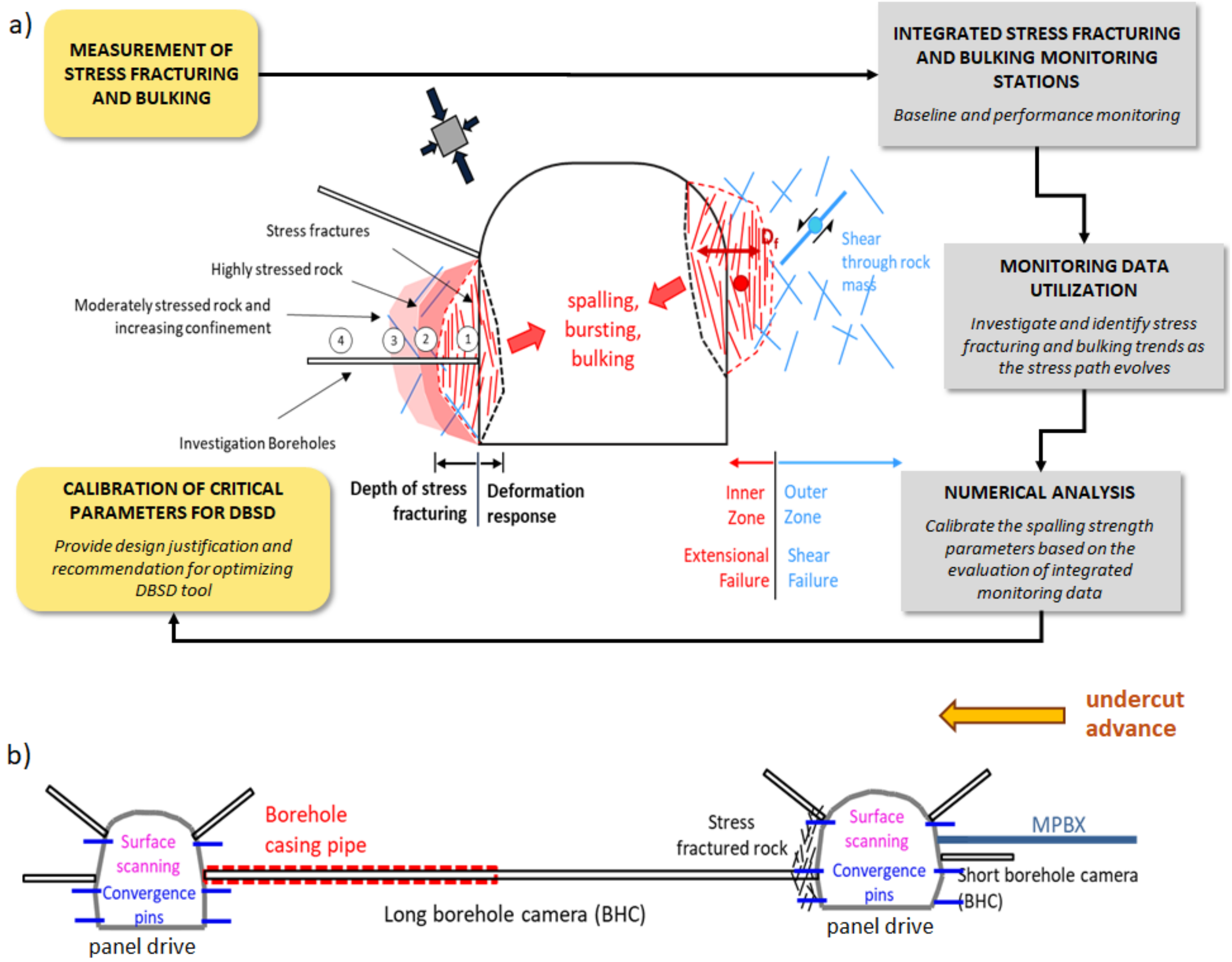


Figure 7 (a) Design of the integrated, purpose-driven monitoring system developed to support deformation-based support design (DBSD) and preventative support maintenance at the deep mill level zone, illustrating the complementary roles of borehole camera (BHC) surveys and multipoint borehole extensometers (MPBX) for mapping depth of stress fracturing and LiDAR and convergence measurements for quantifying bulking; (b) Section view of the monitoring layout illustrating the use of long boreholes drilled from the intact pillar side to maintain BHC access, enabling continued mapping of the depth of stress fracturing even after damage on the excavation side restricts access from the fractured pillar face

The deployment of this integrated system confirmed that stress redistribution associated with undercut advance is the primary control on both fracturing and bulking, while also highlighting the influence of mining geometry and geotechnical domain on the magnitude and progression of damage. Consistent with earlier observations, stress fracturing was shown to precede and govern the onset of bulking, reinforcing its role as the key driver of deformation demand. These observations were used by Primadiansyah et al. (2026) to establish a composite predictive relationship linking stress level, fracture depth and displacement demand, capturing the transient evolution of bulking as a function of proximity to the undercut and cave-induced stress conditions (Figure 8). When implemented in the GSST, this calibration, incorporating crack initiation and spalling limits (Diederichs et al. 2004; Eberhardt et al. 2016) within a confinement-dependent spalling criterion (Rahjoo & Eberhardt 2024), improved the prediction of displacement demand and enabled forecasting of PSM with a lead time of several months, with predicted displacements within approximately 20 mm of measured values before intervention.

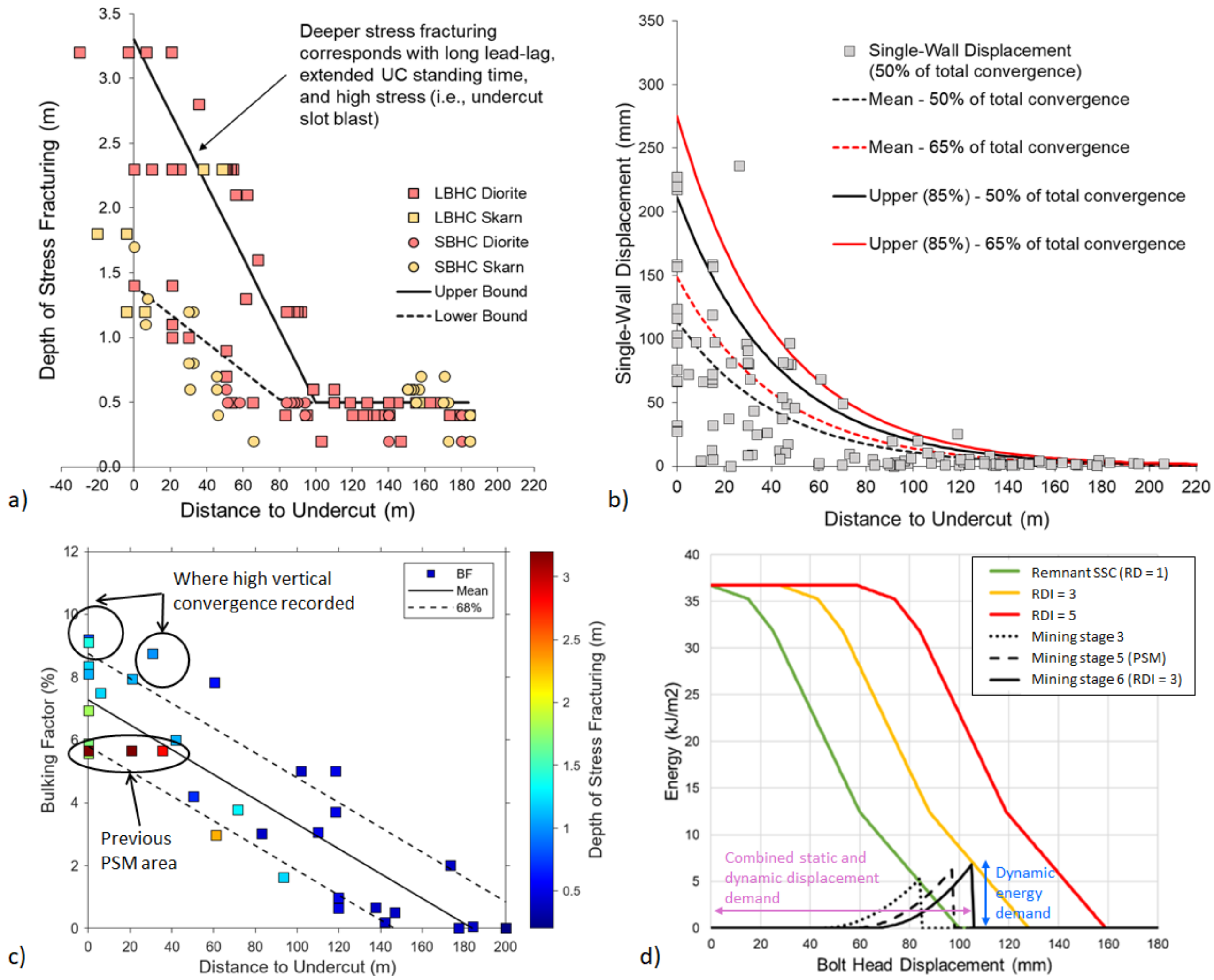


Figure 8 (a) Long-term evolution of stress fracturing depth from borehole camera (BHC) surveys across the deep mill level zone Panel Block 2 extraction level; (b) Corresponding single-wall displacement from convergence measurements; (c) Derived bulking factor, defined as total wall displacement divided by fracture depth, plotted against distance from the undercut and coloured by maximum fracture depth; (d) Energy–displacement response for successive mining stages relative to support system capacity (SSC), showing acceptable (green), marginal (yellow), and unacceptable (red) performance thresholds, where Stage 3 reaches the remnant SSC (FS ≈ 1.0) with acceptable displacement, Stage 5 exceeds design capacity without reaching RDI 3, and Stage 6 intersects the RDI 3 threshold, indicating support failure. Modified after Primadiansyah et al. (2026)

4 Numerical modelling of spalling and strainbursting

Numerical modelling plays a central role in forecasting rock mass behaviour and evaluating ground support performance. Yet, conventional continuum and equivalent-continuum approaches remain limited in their ability to explicitly capture brittle fracturing and damage processes, particularly the transition from stable spalling to dynamic strainbursting. To address this gap, Roy & Eberhardt (2025) adopted a bonded block modelling (BBM) framework in which the rock mass is represented as an assembly of rigid blocks connected by breakable contacts governed by a physically based constitutive law (Plesha & Aifantis 1983; Potyondy & Cundall 2004). This formulation allows extensional fracture initiation, propagation, coalescence and post-peak bulking to emerge naturally from the interaction of blocks, rather than being imposed through predefined failure criteria (Gao et al. 2019; Lavoie et al. 2022).

Central to their approach, Roy & Eberhardt (2025) implemented a linear contact softening (LCS) strength model and identified the appropriate type and magnitude of damping to provide a physically consistent means of controlling energy dissipation while preserving realistic strain wave propagation and momentum transfer. The LCS model enables explicit control over post-peak softening and the rate of strain energy release at the contact scale. At the same time, combined damping dissipates energy in a directional manner without suppressing block motion or distorting wave transmission, thereby allowing realistic simulation of rupture dynamics and fragment interaction.

A key innovation of this methodology is that both spalling and strainbursting emerge within a single unified modelling framework (Figure 9a), governed by rock properties, stress path, and boundary conditions rather than being prescribed *a priori*. Parametric analyses (Figure 9b) show that strength, stiffness, and brittleness control the magnitude of stored strain energy and its release during rupture, with lower energy release producing progressive, gravity-driven spalling and higher energy release generating energetic strainbursting. The simulated responses align well with established indices such as the dynamic rupture potential (Figure 9c), confirming that the model captures the transition from stable to dynamic brittle failure.

The BBM framework was further validated at the tunnel scale through calibration against laboratory data and comparison with DMLZ field observations, including stress-fracturing depth, displacement evolution, bulking and support response. The model captures both quasi-static loading from abutment stress development and transient dynamic loading from strainbursting, enabling direct evaluation of support performance under realistic mining conditions. Critically, it reproduces the cumulative effects of repeated strainburst events as the undercut abutment stress approaches and passes over the tunnel (Figure 10a), showing how successive loading progressively consumes deformation capacity (Figures 10b–10d). This provides a mechanistic basis for integrating DBSD and PSM into numerical analysis.

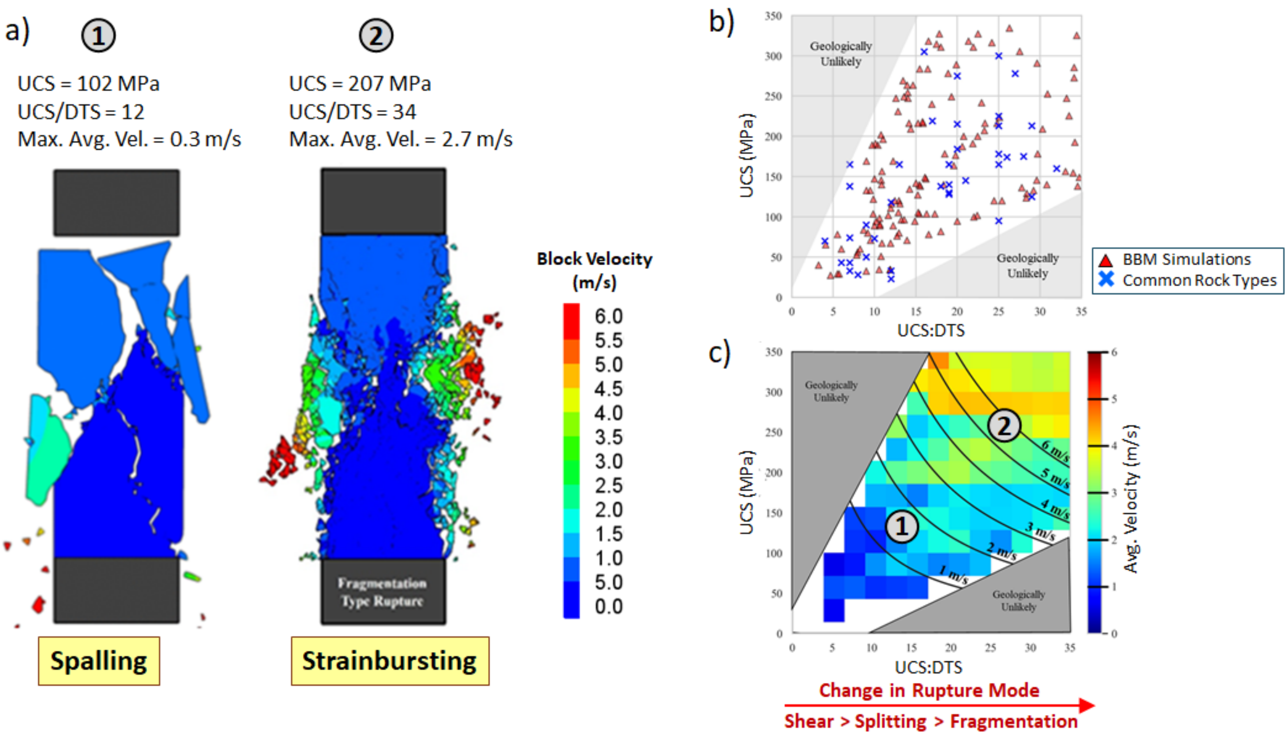
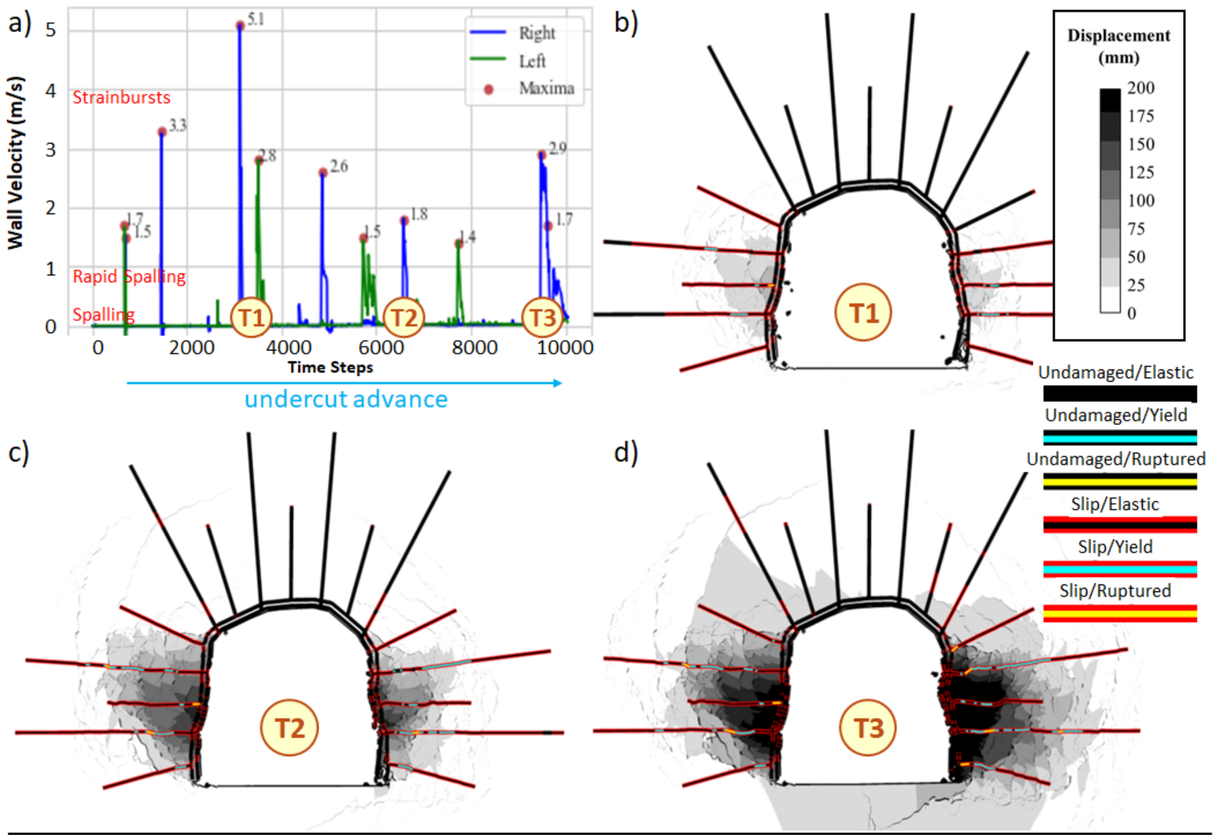


Figure 9 **(a) Bonded block modelling (BBM) simulations showing the transition from spalling to strainbursting as a function of rock brittleness; (b) Parametric analysis results are compared with common rock properties from testing reported by Carter & Marinos (2020) using uniaxial compression (UCS) and direct tension (DTS) relationships; and (c) Simulated ejection velocities mapped onto Diederichs (2018) dynamic rupture potential chart, which shows good agreement with expected behaviour, with velocity-DRP trends confirming the BBM model's ability to reproduce both spalling and strainbursting behaviour. Modified after Roy & Eberhardt (2025)**



e)

Base	2.4 m long, 25 mm, resin grouted rebar (1.3x1.3 m spacing)	4 m long, 15.2 mm, cement-grouted tensioned cables (1.3x1.3 m spacing)	5.6 mm welded wire mesh	150 mm FRS
Heavy	2.4 m long, 25 mm, resin grouted rebar (1.0x1.0 m spacing)	4 m long, 17.8 mm, cement-grouted tensioned cables (1.0x1.0 m spacing)	8.0 mm welded wire mesh	150 mm FRS

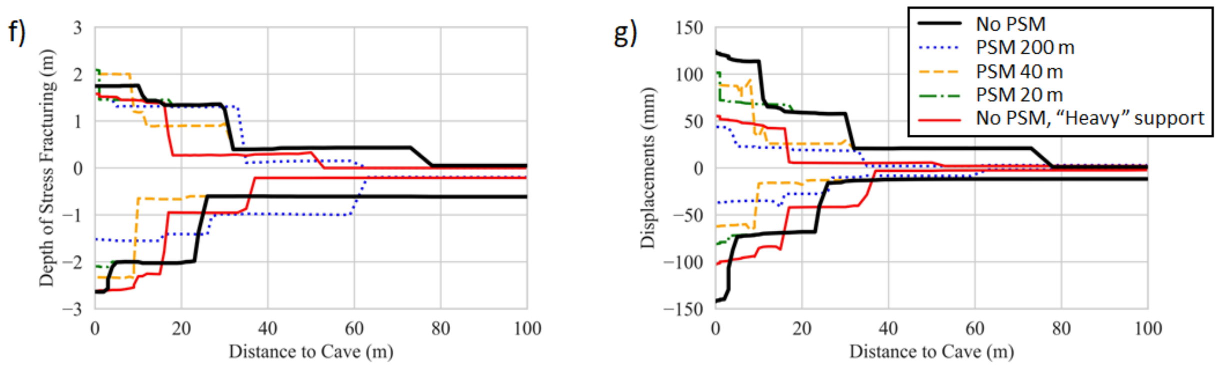


Figure 10 Sequential bonded block modelling showing (a) multiple stress-induced strainburst events of varying severity, reported by maximum wall velocity (showing spalling, rapid spalling and strainbursting thresholds), impacting the same supported tunnel as the undercut advances and passes over the excavation; (b–d) progressive rock mass bulking and associated support damage from the cumulative strainburst sequence; (e) simulated support systems; and (f–g) benefits of preventive support maintenance (PSM) through the addition of three 6 m cables in the ribs, comparing PSM installed at different distances from the cave front. Modified from Roy (2025)

The simulations further show that stress-fracturing depths follow broadly similar trends across support configurations, indicating limited control by support type (Figure 10f). In contrast, displacement and bulking are strongly influenced by support configuration and timing (Figure 10g). Early PSM installation at 200 m from the advancing cave front, before significant straining of the base support, was most effective in reducing displacement and bulking, with a modest reduction in stress-fracturing depth. PSM installed at 40 and 20 m from the advancing cave front also reduced displacement and bulking relative to the base case, although stress-fracture depths remained similar.

These findings challenge common assumptions about rock-support interaction in high-stress environments. Consistent with DMLZ observations, the BBM results show that conventional support systems, such as shotcrete, rockbolts and mesh, do not provide uniform confinement and exert limited control over stress-fracturing depth. Instead, stress fracturing is governed primarily by the evolving stress environment, whereas support functions to control bulking and retain fractured rock. Stiff support elements help suppress early bulking as the stress-fractured skin develops, whereas overly compliant systems permit rapid deformation and early loss of containment. However, stiffness alone is insufficient under repeated loading, as support capacity progressively degrades with increasing bulking and deformation demand.

The results also emphasise the need for a staged support response, load sharing and interaction with the evolving damage zone. Effective systems combine stiff, near-field reinforcement, such as resin-grouted bolts and shotcrete, with longer, more ductile elements, such as cables, that progressively engage as deformation accumulates, forming a 'gabion'-type support system (Kaiser & Moss 2021). Although concerns are often raised about brittle failure of stiff reinforcement, modelling and field observations indicate that stress fracturing more commonly causes progressive debonding than widespread bolt rupture. The transition from split sets to resin-grouted bolts at the PB1 undercut level markedly improved support performance, although increasing damage depth with cave advance ultimately required PSM. Support geometry is also critical: wider bolt and cable spacing was associated with greater surface displacement and reduced confinement between support elements, whereas closer reinforcement spacing improved load transfer and surface support performance. For excavations with shorter or lower-magnitude abutment exposure, stiff systems alone may still be effective for controlling stress fracturing and moderate strainbursting.

Finally, the BBM simulations provided quantitative insights into the relationships between stress fracturing, bulking displacement and support demand, thereby reinforcing the DBSD framework. Because support demand is path-dependent, damage sequence and accumulation govern system response in ways that single-event or static design approaches cannot capture. This allows deformation thresholds to be identified before support performance degrades rapidly, providing a rational basis for scheduling PSM before critical loss of capacity.

5 Conclusion

This paper synthesises a multi-year, operations-focused research program that integrates field observations, geotechnical monitoring and advanced numerical modelling to improve strainburst hazard management and support design in deep cave mining. The cave mining setting is distinguished by the advancing undercut, which creates a moving abutment stress field that repeatedly loads extraction level excavations as the cave propagates. At greater depths and in stronger, more massive rock, this promotes repeated strainbursting and cumulative stress-driven damage. These processes are poorly captured by conventional empirical design methods and continuum-based numerical tools, which were developed largely for shallow or structurally controlled conditions and do not explicitly represent brittle fracture, energy storage and release, cumulative damage, or the deformation demands governing deep excavation performance.

Against this backdrop, the paper advances the understanding and management of rockbursts through an integrated, mechanistic, data-driven and field-validated framework. Central to this advancement is the rigorous identification of strainbursting as the dominant rockburst mechanism during undercut advance. At the DMLZ, this was demonstrated through a database-driven analysis linking observed damage, seismicity and mining activity. By resolving both the mechanism and its triggers, the work shifts the design focus from externally driven dynamic loading to internally driven stress fracturing, repeated strainbursting, and the progressive excavation damage and bulking deformation that develop as the abutment stress field moves across the extraction level footprint.

A key contribution is the development and implementation of purpose-designed monitoring systems integrated with DBSD and PSM. By measuring both stress-fracturing depth and excavation bulking, the monitoring framework captures the progressive damage processes governing excavation response. Demonstrating that stress fracturing precedes and drives bulking deformation is a major practical advance, enabling damage depth to serve as a leading indicator of instability, deformation demand and support performance. When embedded within operational tools such as the DMLZ's GSST, these relationships allow support demand and PSM requirements to be forecast with meaningful lead time, supporting a transition from reactive to proactive ground control.

Equally significant is the development and validation of a BBM framework capable of reproducing both spalling and strainbursting as emergent behaviours. This allows brittle fracture, energy release, fragmentation and directional bulking to arise directly from model physics rather than being imposed. By simulating repeated strainburst and stress-damage events under the evolving abutment stress field generated by undercut advance, the framework provides new insight into the cumulative nature of excavation damage in deep cave environments. The results demonstrate that support performance is governed not only by dynamic capacity, as traditionally emphasised in stoping environments, but also by progressive deformation demand associated with stress fracturing, bulking and repeated loading. By reproducing the path-dependent consumption of support capacity, the framework provides the mechanistic basis for integrating DBSD and PSM into support design and numerical analysis.

Collectively, the integration of mechanism identification, monitoring, design and modelling represents a significant advancement in rock engineering and deep mining practice. It enables engineers to move beyond empirical, single-event design approaches toward a predictive and adaptive framework that explicitly accounts for evolving stress conditions, repeated strainbursting and cumulative brittle damage and deformation. By linking mechanism, measurements and modelling within a unified design framework, this work improves the reliability of excavation performance assessment and ground control decision-making, enhancing safety and providing a scalable methodology for managing strainburst hazards in the next generation of deep cave mining operations.

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