

https://dspace.org/

Evaluating destress blasting for rockfracture and rockburst prediction indeep level hardrock mining

T Zvarivadza; C Yi; S Dineva; M Khandelwal; Bekir Genc ...

SOUTHERN AFRICAN INST MINING METALLURGY
https://hdl.handle.net/10539/45520
WOS

Downloaded from a DSpace repository. https://dspace.org/

Evaluating destress blasting for rock fracture and rockburst prediction in deep level hardrock mining

by T. Zvarivadza[1], C. Yi[1], S. Dineva[1], M. Onifade[2], M. Khandelwal[2], B. Genc[3]

Affiliation:
[1]Division of Mining and Geotechnical Engineering, Luleå University of Technology, Sweden
[2]Institute of Innovation, Science and Sustainability, Federation University Australia, Australia
[3]School of Mining Engineering, University of the Witwatersrand, South Africa

Correspondence to:
B. Genc

Email:
bekir.genc@wits.ac.za

Dates:
Received: 6 Mar. 2025
Revised: 21 Apr. 2025
Accepted: 2 May 2025
Published: June 2025

How to cite:
Zvarivadza, T., Yi, C., Dineva, S., Onifade, M., Khandelwal, M., Genc, B. 2025. Evaluating destress blasting for rock fracture and rockburst prediction in deep level hardrock mining. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 125, no. 6, pp. 273 –298

DOI ID:
https://doi.org/10.17159/2411-9717/3685/2025

ORCiD:
T. Zvarivadza
http://orcid.org/0000-0003-1014-0405
C. Yi
http://orcid.org/0000-0002-5872-5173
S. Dineva
http://orcid.org/0000-0001-9419-2207
M. Onifade
http://orcid.org/0000-0001-9933-266X
M. Khandelwal
http://orcid.org/0000-0003-0368-3188
B. Genc
http://orcid.org/0000-0002-3943-5103

Abstract

Deep level hardrock mining faces increasing challenges from elevated in situ stresses and associated rockbursts. This study aims to develop a systematic framework for evaluating destress blasting effectiveness, with a focus on deep Swedish hardrock mines. The methodology integrates a critical review and adaptation of global best practices: advanced numerical modelling (static and dynamic simulations), field-based rock fracture monitoring using ground penetrating radar and borehole imaging, and application of rockburst prediction criteria including the strain energy storage coefficient (F), brittle shear ratio, and burst potential index. Geostatistical simulations, machine learning models, and industrial internet of things-based, real-time monitoring are proposed to enhance predictive accuracy, model calibration, and operational adaptability. Key findings show that effective destress blasting evaluation requires multi-modal integration of numerical outputs, field observations, microseismic trends, and uncertainty quantification, accounting for site-specific geological variability and dynamic stress redistribution. The study advances the field by proposing a predictive, feedback-driven evaluation framework tailored for deep Swedish mining conditions, capable of improving proactive rockburst risk management. It offers both practical tools for mining practitioners to optimise stress management, reduce seismic hazards, and enhance excavation safety, and academic foundations for future refinement of destress blasting models, geotechnical monitoring strategies, and adaptive design protocols. This research contributes to safer, more efficient deep mining operations by bridging gaps between theoretical modelling, empirical monitoring, and real-time, data-driven blast design optimisation strategies.

Keywords

destress blasting evaluation, deep-level hardrock mining, numerical modelling, rockburst prediction criteria, seismicity, geostatistical simulation, real-time monitoring (IIoT)

Introduction

Deep level hardrock mining presents significant geomechanical challenges, particularly due to the elevated stress conditions that lead to strain bursts, rockbursts, and structural failures (Li et al., 2017; Wagner, 2019; Małkowski, Niedbalski, 2020; Swan, Li, 2023; Cai, 2024; An, Mu, 2025). As mining operations progress to greater depths, the management of stress redistribution becomes increasingly critical to ensuring the safety of workers and the stability of underground excavations. Traditional support and stress management techniques often become insufficient to control extreme stress concentrations and associated rockburst hazards as mining progresses to ever greater depths. This reality necessitates the exploration of proactive rock engineering methods capable of modifying the in situ stress field before failure occurs. Among these methods, destress blasting has emerged as a particularly promising approach for mitigating dynamic failure risks by strategically redistributing stress ahead of excavation faces. Destress blasting is a proactive rock engineering technique, which has gained recognition as a viable method for mitigating the risks associated with mining-induced seismicity and dynamic rock failures (Tang, 2000; Sainoki et al., 2017; Vennes, Mitri, 2017; Drover et al., 2018; Drover, Villaescusa, 2019; Vennes et al., 2020; Mertuszka et al., 2022; Shnorhokian, Ahmed, 2024a; Shnorhokian, Ahmed, 2024b). The fundamental principle of destress blasting is to precondition the rockmass ahead of mining faces, reducing its stored elastic strain energy and altering the in situ stress field to minimise the likelihood of catastrophic rock failures. Despite its engineering value, the practical application of destress blasting in deep hardrock mines remains a complex engineering challenge. Variations in geological conditions, rockmass properties, and stress anisotropy necessitate site-specific optimisation of blast design parameters, including charge distribution, hole spacing, initiation sequences, and delay timing. Whereas field observations and empirical studies have demonstrated the benefits of destress blasting in

alleviating rockbursts and seismic risks, comprehensive evaluations of its effectiveness require effective methodologies that integrate numerical modelling, field instrumentation, and microseismic monitoring.

This study focuses on evaluating the performance of destress blasting in deep hardrock mining environments, with an emphasis on Swedish mining operations. Although extensive research on destress blasting has been conducted in other mining regions such as Canada (Cullen, 1988; Labrie et al., 1997; O'Donnell, 1999; Tang, 2000; Sampson-Forsythe et al., 2002; Andrieux et al., 2003; Andrieux, Hadjigeorgiou, 2008; Sainoki et al., 2017; Vennes, Mitri, 2017; Yao et al., 2019; Drover , Villaescusa, 2019; Vennes et al., 2020, among others) and South Africa (Hill et al., 1966; Malan et al., 1997; Toper et al., 1997; Toper et al., 2000; Toper, 2002; Toper et al., 2003; Durrheim, 2010; Modisha, Zvarivadza, 2015; Sengani, Amponsah-Dacosta, 2018; Sengani, Zvarivadza, 2018a; Sengani, Zvarivadza, 2018b; Zvarivadza, Sengani, 2018; Sengani et al., 2019; Sengani, 2020a; Sengani, 2020b, among others), where several important regional differences must be recognised. Even though valuable knowledge has been gained from extensive studies conducted in South African gold mines and Canadian hardrock operations, the direct application of these strategies to the deep hardrock mining environment of Sweden remains underexplored. Differences in geological structure, rockmass competency, stress regimes, and seismic response necessitate careful regional adaptation of destress blasting principles. Despite global advancements, there remains a critical research gap, i.e., a lack of systematically validated methodologies for evaluating the effectiveness of destress blasting under the unique geological and operational conditions found in Swedish deep hardrock mines. Current numerical modelling and field monitoring techniques are not fully calibrated to the rockmass conditions typical of Sweden. Without adaptation and validation, existing methods risk misrepresenting destress blasting performance, compromising operational safety and efficiency. The study aims to address the research gap by investigating the most suitable methodologies for assessing the efficiency of destress blasting under deep underground mining conditions. Comprehensive evaluations of destress blasting must consider both site-specific geological conditions and evolving monitoring technologies to ensure that methods are appropriately adapted for local conditions.

Some research gaps in the literature

Destress blasting has been studied in various underground mining contexts, with notable contributions focusing on its theoretical basis, practical implementation, and field performance assessments. Early studies by Roux et al. (1957), Cook et al. (1966), and Blake (1972) introduced the concept of preconditioning brittle rockmasses to mitigate rockburst hazards. Subsequent investigations expanded on these ideas, developing numerical models and field validation techniques to refine destress blasting strategies (Miao et al., 2022; Tang, Mitri, 2001; Andrieux, Hadjigeorgiou, 2008). These studies highlighted key design considerations, including the need for appropriate explosive energy levels, borehole configurations, and initiation sequences tailored to specific geological settings. One of the primary research gaps in existing literature is the challenge of accurately predicting and quantifying the effectiveness of destress blasting. Traditional evaluation methods have relied on empirical observations and qualitative assessments, which, in as much as informative, lack the predictive capability needed for optimising blast designs in variable rockmasses. More recent studies have employed numerical modelling approaches, such as finite element and discrete element methods, to simulate stress redistribution and fracture propagation resulting from destress blasting (Miao et al., 2022). These models, however, often require extensive calibration and may not fully capture the complex interactions between pre-existing geological discontinuities and blast-induced stress waves. Another limitation in current research is the lack of standardised criteria for assessing destress blasting performance. Various metrics have been proposed, including stress dissipation factors, elastic modulus reductions, and seismic event reductions (Sainoki et al., 2017). The relative effectiveness of these criteria remains an open question, particularly in the context of different mining environments. Despite microseismic monitoring having been used to track stress changes following destress blasting, there is a need for more refined methodologies that integrate multiple data sources, including geophysical surveys, borehole imaging, and numerical simulations to provide a comprehensive evaluation framework.

Scope, objectives, and contributions of the study

This study systematically evaluates the effectiveness of destress blasting in deep hardrock mining, with a specific focus on Swedish underground mines. It consolidates existing research on numerical modelling, evaluation techniques, and seismic monitoring to understand how destress blasting influences stress redistribution, rockmass response, and seismic hazard mitigation. The study critically reviews numerical simulations, comparing static and dynamic approaches, and assesses key design parameters such as blast energy distribution and borehole spacing. It also examines geophysical monitoring techniques, including ground penetrating radar (GPR) and borehole periscopes, as well as seismic monitoring and rockburst prediction criteria, such as the strain energy storage coefficient (F), brittle shear ratio (BSR), and burst potential index (BPI). The study also proffers some innovative destress blasting evaluation methods incorporating geostatistics, machine learning, and IIoT real-time monitoring. The research highlights optimisation strategies and decision-support frameworks that improve destress blasting applications, drawing crucial perspectives from global best practices. The study provides a structured framework for evaluating destress blasting efficiency by integrating theoretical models, empirical assessments, and monitoring techniques. Unlike previous studies that focus solely on numerical simulations or qualitative observations, this research offers a holistic approach to stress relief assessment. It also addresses a critical knowledge gap by exploring how destress blasting can be adapted to the unique geological and operational conditions of Swedish hardrock mines. The findings of the study contribute to improved safety, enhanced operational decision-making, and the refinement of destress blasting strategies in deep underground mining.

Several approaches can be used to evaluate the efficiency of a particular chosen destress blasting design. Most of the approaches are based on the ability of the destress blast design to reduce rockburst potential (burst proneness) of the rockmass or on reducing the deformation potential of the exposed rockmass after excavation. Each approach utilises key parameters associated with rock bursting which can be assessed before and after the implementation of a chosen destress blasting design. This paper dwells on those key evaluation techniques, which are suitable for informing destress blasting practice in deep underground hardrock mines of Sweden. It is of significant importance to use at least two different approaches to assess the performance of a destress blast design to consolidate confidence in the performance

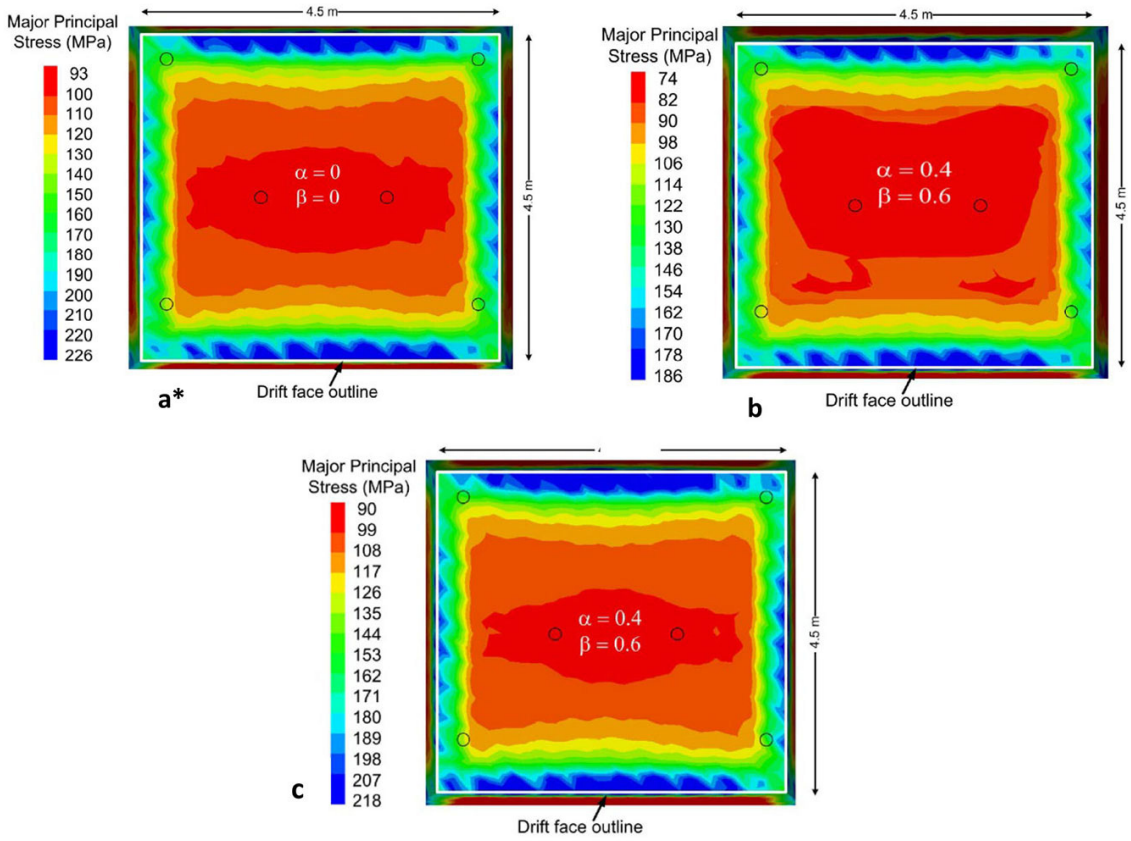
results. Through its coverage, the study contributes to the scientific advancement of stress management strategies in deep mining and offers practical guidance for safer, more efficient underground operations in Sweden.

Numerical modelling

Calibrated numerical models can be used to assess the efficiency of an adopted destress blast design. Several researchers have evaluated destress blast designs through numerical modelling with a view to select the most appropriate design for a given set of mining conditions (Sui et al., 2025; Shnorhokian, Ahmed, 2024a; Hashemi et al., 2023; Fuławka et al., 2022a; Hashemi, Katsabanis, 2021; Baranowski et al., 2019; Drover et al., 2018; Sainoki et al., 2017; Andrieux, Hadjigeorgiou, 2008; Saharan, 2004; Toper et al., 2003; Toper, 2003; Borg, 1988). The discussion on numerical modelling and its application in destress blasting can be lengthy and extensive. Miao et al. (2022) provide a detailed review on the application of numerical modelling in destress blasting design. They note that two main modelling approaches, static and dynamic, are commonly employed - the static method modifies rockmass properties to simulate destress blasting's impact, while dynamic modelling focuses on the dynamic fracture process without predetermined damage. Miao et al. (2022) compare different destress blasting numerical methods, including continuum-based, discrete-based, and coupled methods. Other key issues they explore in detail include the fracture mechanism, the assessment of destress blasting designs efficiency, factors influencing destress blasting efficiency, and highlighting the challenges and difficulties associated with numerical modelling of destress blasting.

To maintain some modicum of brevity of this paper, and yet cover key issues relevant to the successful use of numerical modelling as a destress blasting design tool, this discussion zooms into and shines the spotlight on the work by Sainoki et al. (2017). Sainoki et al. (2017) warn that traditional ways of modelling, which assume that the damage zone induced by the destress blast is spread over the whole drift face, may result in overly optimistic destress blast results. This is a result of the models predicting lower than actual resultant stresses around the destressed excavation due to oversimplification of the prevailing conditions in the rockmass. To mitigate against this, Sainoki et al. evaluated the damage of each hole individually and obtained results more reflective of prevailing ground conditions after preconditioning as shown in Figure 1. Assessing the major principal stress (MPa) legend for each case in Figure 1, it can be noted that the stress drops from a maximum of 226 MPa (before destressing) to 186 MPa and 218 MPa for the traditional modelling case and the individual damage zones modelling case, respectively. This shows that the traditional modelling approach potentially underestimates the peak major principal stress after destress blasting by about 32 MPa in this scenario.

In the destress blast evaluation model, Sainoki et al. (2017) adopted the concept of rock fragmentation factor (α) as introduced by Blake (1972) as per Equation 1. The concept is based on the observation that effective destress blasting leads to the widespread



*Note that α for before destressing case (case a) should be 1 since the elastic modulus should be relatively constant before destressing – this is a typo error from Sainoki et al. (2017)

Figure 1—Drift face contours for Sigma 1 (Sainoki et al., 2017): a) before destressing, b) after destressing (traditional modelling) c) after destressing (individual damage zones modelling)

extension of cracks existing in the rockmass and generation of more cracks, leading to significant stress release ahead of the mining drift face. When this happens, the stiffness of the rockmass is significantly reduced, resulting in a much lower elastic modulus compared to the elastic modulus before destressing. As expected, the elastic modulus of the rockmass remains about the same when α is 1; that is when there is little to no rock fragmentation before destressing. In rock mechanics terms, the softening of the rock due to action of stress can be explained using the Poisson's effect. The changes in Poisson's ratio before and after destress blasting, can also be used to evaluate the efficiency of a destress blast design using Equation 2, as suggested by Tang and Mitri (2001) as per Equation 2. When α is 1 (relatively unfragmented rockmass), the Poisson's ratio remains almost the same. When α is 0 (significantly fragmented rockmass) the Poisson's ratio almost doubles, signifying enormous softening of the rockmass due to destress blasting.

Sainoki et al. (2017) also use the concept of stress dissipation factor (β) developed by Tang and Mitri (2001) to assess destress blasting efficiency (Equation 3). When β is 1, the stress after destress blasting is reduced significantly, showing that the high stress in the immediate vicinity of the mining drift face has been dissipated further into the rockmass, reducing the strain burst risk at the mining face. $\beta = 0$ indicates a scenario where the stress in the immediate vicinity of the mining face remains the same, that is when no destress blasting is employed.

$$E_{after} = E_{before}\alpha \quad [1]$$

$$\upsilon_{after} = \upsilon_{before}(2 - \alpha) < 0.5 \quad [2]$$

$$\sigma_{after} = (1 - \beta)\sigma_{before} \quad [3]$$

Practical implementation of several different destress blasting designs is obviously expensive, hence the need to simulate several different destress blasting designs using numerical models to select a few suitable designs to physically assess. The field tests of the few suitable designs allow practitioners to choose the best destress design for a particular set of geotechnical ground conditions. Numerical modelling in three dimensions facilitates the identification of underground areas prone to rockbursts and, therefore, aids design of underground constructions (Kaiser, Cai, 2012). It cannot be overemphasised that numerical modelling to prescribe a suitable destress blasting design for a deep hardrock mining operation should follow the standard modelling stages (procedure) posited by Starfield and Cundall (1988).

Although Sainoki et al. (2017) introduced the fragmentation factor (α) and stress dissipation factor (β) to improve evaluation metrics, studies rarely integrate these parameters into real-time, adaptive modelling frameworks. The present study identifies this as a critical gap: linking numerical outputs (e.g., changes in α and β) dynamically to field-monitored seismic responses would enable feedback-driven optimisation of destress blast designs, something not yet systematically achieved. Cross-validation of numerical predictions with independent fracture network imaging data, such as GPR or borehole periscope observations is critical for a successful destress blasting strategy. This study supports multi-modal integration, combining numerical simulations with direct fracture monitoring and seismic monitoring trends, to holistically evaluate and refine destress blasting performance.

Rock fracture monitoring ahead of the excavation face

To gauge the effectiveness of an adopted, destress blast design, evaluation of the rock fracturing ahead of the mining face after the blast can be done. Effective destress blasting is expected to create or extend a network of fractures, which connect the destress blast holes sockets. This is critical in assessing the most optimum number of destress blast holes to use with the production blast holes. The network of fractures provides a path for stress relief from the immediate vicinity of the blasting face into the rockmass. The intensity of fracturing ahead of the mining face due to destress blasting can be assessed using ground penetrating radar, borehole periscope, and mining face drill core discing observations.

Ground penetrating radar

In the study of application of destress blasting to manage seismic hazard, Sengani (2020b) noted that the application of the ground penetration radar technique successfully identified seismic and non-seismic hazards, which could not be identified through conventional and numerical evaluations in hardrock mining. Fractures in the rockmass and geological structures causing breaks in the rockmass (discontinuities) can be picked using the GPR technique. The technique uses the geophysics approach of rapidly reflecting electromagnetic waves at high resolution in a scan target, providing vital information about the distribution of rockmass discontinuities. Sengani (2020b) provides an account of the theoretical background of the GPR and its application in different fields including archaeology, construction, mining, exploration of gem tourmaline pockets and vugs, identification of voids and cavities, and assessing the depth of a water table. Sengani (2020b) notes that, although GPR has been extensively used in mining and construction (Shi et al., 2018; Liu et al., 2018; Hao et al., 2016; Fedorova et al., 2016; Moradipour et al., 2015; Ralston, Strange, 2015; Lualdi, Zanzi, 2004; Jha et al., 2004; Toper et al., 1999; Ralston et al., 2001; Ralston, Hainsworth, 1999; Hainsworth et al., 1999; Murray et al., 1996; Noon, 1996; Chufo, Johnson, 1993; Mowrey et al., 1995; Daniels, 1980; Ellerbruch, Belsher, 1978), there are few studies, which cover particular application of GPR in rock mechanics (Sengani et al., 2019; Sengani, Zvarivadza, 2018a; Sengani, Amponsah-Dacosta, 2018; Sengani, Zvarivadza, 2017; Toper, 2003; Grodner, 2001). Figure 2 illustrates the application of GPR in a mining tunnel.

The GPR equipment is shown in Figure 3.

The intensity of fracturing ahead of the mining face can be assessed using colour coding, as presented in Table 1. Dark red colour indicates a fracture frequency of more than 20 fractures per metre and dark blue colour represents a fracture frequency of less than 5 fractures per metre.

Example GPR scans for destress blasting using four destress blast holes and five destress blast holes on the mining face for deep level hardrock mining in South Africa are presented in Figure 4 and Figure 5, respectively. Using Table 1 to interpret the results, it can be seen that more intensive fracturing ahead of the mining face is achieved when using five destress blast holes compared to four destress blast holes.

It then becomes critically important to choose the optimum number of destress blast holes or blast hole spacing to achieve optimum destress blasting results. It should be noted that using more holes than necessary leads to unnecessary costs and waste of time in drilling the additional holes.

Understanding both the advantages and disadvantages of using GPR allows for a balanced assessment of its suitability in specific underground mining contexts. Consideration of geological conditions, expertise in data interpretation, and the specific goals

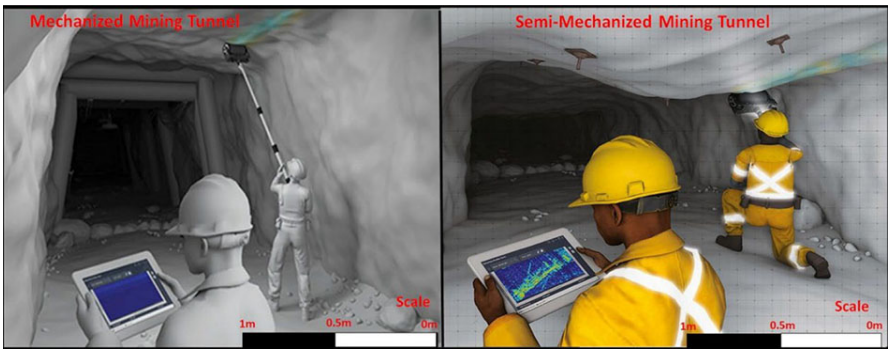


Figure 2—Illustration of GPR application in a mining tunnel (mechanised and semi-mechanised) (modified by Sengani (2020b) after Reutechmining (2017)



Figure 3—Ground Penetrating Radar units (from Sengani et al., 2019)

of the mining operation are crucial in determining the effectiveness of GPR for assessing rock fracturing ahead of the mining face. The advantages and disadvantages of GPR are presented in Table 2.

A close look at some practical applications and case studies demonstrating GPR effectiveness

GPR has been increasingly applied in underground mining environments to assess rockmass fracturing, evaluate the effectiveness of destress blasting, and detect hazardous geological structures that conventional methods often miss. Several practical examples demonstrate the reliability and operational value of GPR for these purposes. One notable application was documented in great technical detail at Mponeng Mine (in South Africa), one of the deepest hardrock gold mines in the world, by Thebethe, (2018). Van Schoor et al. (2022) report on the successful application of GPR in South African deep platinum and gold mines to detect and characterise fracture intensities ahead of mining faces. Momayez et al. (1996) present the application of GPR in Canadian mines to enhance safety, reduce costs, and improve productivity. They note that, in the Kidd Creek base metal mine, GPR was used to monitor the stability of a sill pillar, detect sulphide pockets, assess

Table 1

Rockmass fracturing intensity interpretation using the ground penetrating radar (from Sengani, 2020b)

Fracture frequency/ metre	Risk profile	Colour coding
<5	High strainburst risk, rockmass not fractured/yielded	
5 – 10	Medium strainburst risk, rockmass beginning to fracture/yield	
10 – 20	Low strainburst risk, rockmass has fractured/yielded	
> 20	Very low strainburst risk, rockmass highly fractured/ yielded	

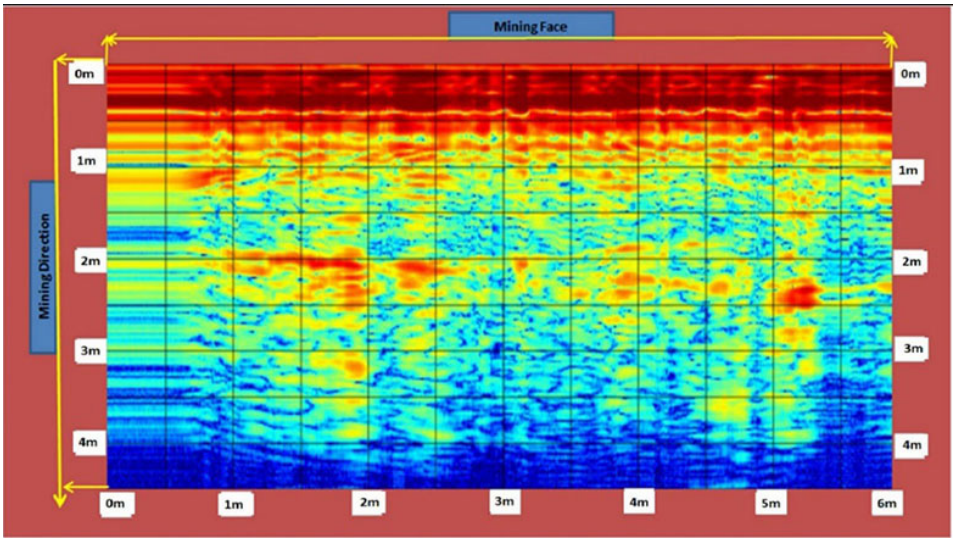


Figure 4—Rock fracturing ahead of the mining face: destress blasting using four destress blast holes (Sengani, 2020b)

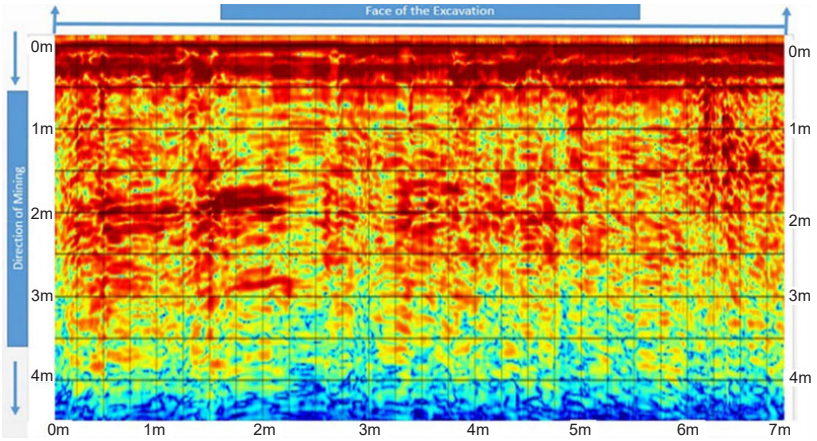


Figure 5—Rock fracturing ahead of the mining face: destress blasting using five destress blast holes (Sengani, 2020b)

Table 2

Advantages and disadvantages of GPR

Advantages		Disadvantages	
Aspect	**Description**	**Aspect**	**Description**
Non-destructive testing	A non-destructive testing method, allowing for the assessment of rock fracturing without causing damage to the rockmass.	Limited depth penetration in certain conditions.	The performance of GPR may be significantly hindered in geological conditions characterised by high conductivity or attenuation. In such environments, GPR may experience signal attenuation, resulting in reduced signal strength and diminished data quality. The technique may encounter limitations in achieving significant depth penetration in certain dense or conductive rock types like iron ore, thereby impacting its overall applicability in these specific geological scenarios.
Real-time imaging	Provides real-time imaging capabilities, enabling continuous monitoring of the subsurface conditions ahead of the mining face.	Resolution variability.	The resolution of GPR can vary based on factors such as frequency and geological conditions, impacting the level of detail in the obtained images.
High resolution	Can offer high-resolution images, allowing for detailed analysis of rock fractures and structures, aiding in accurate characterisation.	Interpretation challenges.	Accurate interpretation of GPR data requires expertise, and the presence of complex geological features can pose challenges in distinguishing fractures from other structures.
Depth penetration	Can penetrate to significant depths, providing information about subsurface conditions at various depths, which is crucial for understanding the full extent of rock fracturing.	Surface roughness influence.	Surface roughness affects the accuracy of GPR by influencing the interaction of radar signals with the fracture surface. The irregularities on the surface introduce complexities such as reflections, scattering, absorption, and diffraction, all of which contribute to distortions in the received signals.
Versatility	Versatile method, which can be used in various geological settings and rock types, making it applicable to a wide range of underground mining scenarios.	Environmental factors.	Environmental factors such as water content in the rockmass can impact GRP performance, especially in water-saturated conditions.
Rapid data collection	Allows for rapid data collection, facilitating efficient and timely decision-making in mining operations	Equipment size and portability.	Some GPR equipment may be bulky, limiting its portability in certain underground mining environments.
Safety enhancement	Helps in identifying potential hazards and unstable rock conditions, contributing to improved safety for underground mining personnel.	Cost of equipment.	The initial cost of GPR equipment can be relatively high, although this may be offset by its efficiency and cost-effectiveness in certain applications.
Cost-effective	Compared to some other subsurface imaging methods, GPR can be a cost-effective solution for assessing rock fracturing, especially in certain geological settings.	Challenges in detecting small-scale fractures.	GPR may encounter difficulties in accurately differentiating small-scale fractures within the rockmass. The resolution limitations of GPR may hinder the detection and characterisation of fractures that are below a certain size threshold, potentially overlooking critical details in the rock structure.
In situ assessment	Enables in situ assessment, providing direct observation on the conditions that the mining face is about to encounter.	Limited performance in highly variable ground conditions variable ground conditions.	The effectiveness of GPR may be compromised in geological settings with high variability in ground conditions. Variations in rock types, moisture content, and composition can lead to unpredictable signal behaviour, making it challenging to obtain consistent and reliable data across diverse geological profiles.

Note: GPR measurements can be susceptible to electromagnetic interference from external sources, such as power lines or electronic equipment. This interference can introduce noise into the radar signals, compromising the quality and reliability of the data obtained, particularly in environments with high electromagnetic activity.

rockfill quality, and identify voids or fractures in filled areas. The technology proved effective in mapping geological structures and evaluating the integrity of underground supports, such as culvert systems (Momayez et al.,1996). These case studies, among many others, collectively validate GPR as a practical, non-destructive, and real-time method, which can be used for evaluating destress blasting effectiveness through rockmass fracturing characterisation and guiding proactive ground control strategies. Although challenges such as signal attenuation in conductive environments remain, advances in GPR antenna technology and data processing have significantly improved its penetration depth and resolution, making it an essential tool in modern deep mining operations.

Borehole periscope

The GPR scan results can be verified using the technique of borehole camera. Rock fracturing ahead of the mining face can also be evaluated using a borehole periscope (camera). The technique can be used to verify the results of the GPR scans. This is a distinctly valuable alternative ,which can be used to detect some of the errors, which may occur due to a malfunctioning GPR. The reverse also applies in verifying borehole camera results using the GPR technique. The borehole camera can detect the fracture frequency from the collar of a borehole all the way up to the end of the borehole. Integrating borehole cameras with GPR has emerged as a powerful method to improve subsurface interpretation in deep underground hardrock mining. In spite of the fact that GPR provides broad detection of geological structures, it is prone to false anomalies due to environmental interference (Dang et al., 2018). Borehole cameras offer high-resolution visual imaging that verifies and refines GPR interpretations by directly observing fractures and discontinuities (Zou et al., 2021; Yuan et al., 2023). This combination addresses the calibration challenges of GPR, enhancing the certainty of features like fault zones and supporting more accurate rockmass modelling (Kulich, Bleibinhaus, 2020). Borehole camera data also enable advanced image processing and automated analysis, further improving reliability (Zou et al., 2021). This integrated approach strengthens subsurface characterisation, optimises mining support design, and enhances operational safety by cross-validating anomalies detected by GPR (Yuan et al., 2023). Together, the methods overcome the individual limitations of each technology, offering a reliable framework for managing geological risks in deep mining environments (Dang et al., 2018; Zou et al., 2021; Yuan et al., 2023; Kulich, Bleibinhaus, 2020).

Sengani and Zvarivadza (2018a) present the application of borehole periscope in the assessment of rock fracturing ahead of deep level hardrock mining faces destressed using destress blasting. Figure 6 illustrates borehole periscope observations of rock fracturing ahead of a mining pillar face destressed using destress blasting. The interpretation of the fracture frequency relative to rockburst potential of the mining face can be done using the criteria suggested by Sengani and Zvarivadza (2017) in Table 3.

As expected, the fracturing is high in the immediate vicinity of the pillar face and decreases towards the pillar core. Table 4 gives the advantages and disadvantages of the borehole camera method.

Drill core observations

The degree of fracturing ahead of the excavation face can also be observed by collecting drill core from the excavation face before and after destress blasting and analysing it, as per Figure 7.

The advantages and disadvantages of the drill core observations method are presented in Table 5.

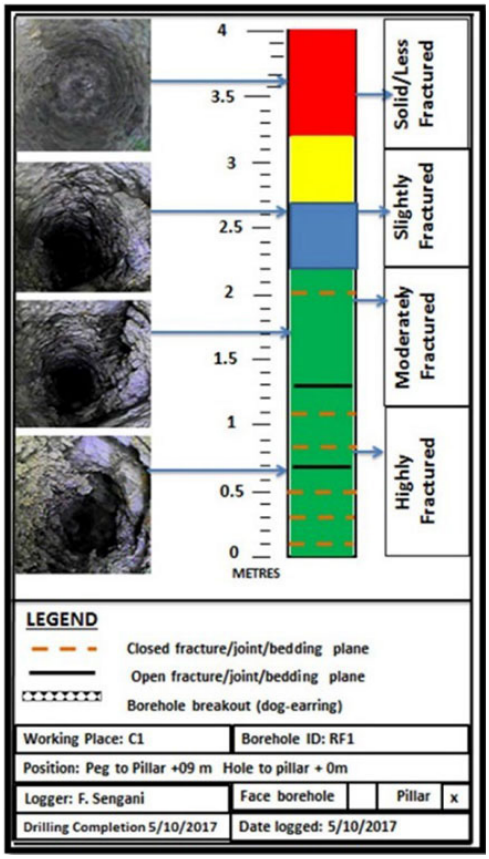


Figure 6—Rock fracturing observation for a mining pillar (pillar face to pillar core orcentre) using a borehole camera (Sengani, 2020b)

Table 3

Fracture frequency interpretation in relation to rockburst potential (Sengani, Zvarivadza, 2017)

Fracture frequency/ metre	Risk profile	Colour coding
<5	High strainburst risk, rockmass not fractured/ yielded	
5–10	Medium strainburst risk, rockmass beginning to fracture/yield	
10–20	Low strainburst risk, rockmass has fractured/ yielded	
>20	Very low strainburst risk, rockmass highly fractured/ yielded	

Key insights on evaluating destress blasting performance using rock fracture monitoring

The evaluation of rock fracturing ahead of the excavation face is a critical aspect in the assessment of destress blast designs within underground mining operations. Various techniques are employed to understand the effectiveness of these designs, each offering unique perspectives into the condition of the rockmass. The discussion revolves around three primary methods: GPR, borehole periscope, and drill core observations.

Table 4

Advantages and disadvantages of the borehole camera method

Advantages		Disadvantages	
Aspect	**Description**	**Aspect**	**Description**
Direct visualisation	Provides direct visual access to the interior of the borehole, allowing for real-time observation and assessment of rock conditions, fractures, and structures.	Limited coverage area.	Has a limited coverage area and may only provide information about conditions within the immediate vicinityof the borehole. This limitation may not capture a comprehensive picture of the entire rockmass.
Detailed inspection	Offers high-resolution imaging, enabling a detailed inspection of rock fracture within the borehole. This level of detail aids in the accurate characterisation of ground conditions.	Dependence on borehole access.	Effectiveness depends on the accessibility of the borehole. In situations where boreholes are sparse or difficult to access, the coverage and applicability of this method may be constrained.
Target analysis	Allows for targeted analysis of specific areas of interest within the borehole, facilitating a focused examination of potential fracture zones and geological anomalies.	Risk of damage or loss.	Borehole cameras may be at risk of damage or loss during deployment, particularly in challenging geological conditions. The fragility of the equipment can impact its reliability and lifespan.
Orientation and dip measurements	Can be equipped with tools for measuring the orientation and dip of fractures. This information is valuable for understanding the geological structure and the potential for rock instability.	Interpretation challenges.	Interpretation of borehole camera data requires expert knowledge, and visual assessments may be subjective. Identifying specific rock types, fracture characteristics, or potential instability may be challenging without the proper geological knowledge.
Real-time data acquisition	Provides real-time data acquisition, enabling immediate decision-making during the drilling process. This can be crucial for adapting mining strategies based on the observed geological conditions.	Time-consuming process.	The deployment and retrieval of borehole cameras can be time-consuming, especially in situations where multiple boreholes need to be inspected. This can impact the efficiency of decision-making in time-sensitive mining operations.
Cost-effective for specific applications	In certain scenarios where targeted borehole inspections are required, borehole cameras can offer a cost-effective solution compared to more extensive geophysical surveys or drilling programmes.	Data storage and analysis.	Managing and analysing the large volume of visual data obtained from borehole cameras can be challenging. Effective data storage and analysis methods are necessary to derive meaningful interpretations from the visual records.
Useful in different borehole sizes	Borehole cameras are available in various sizes, allowing for deployment in boreholes of different diameters.	Limited in detecting microfractures.	May struggle to detect microfractures or hairline cracks that are below the resolution threshold of the camera.
Documentation and record-keeping	Facilitates the documentation and recording of visual data, creating a visual log of subsurface conditions that can be referenced for future analysis or comparison.	Dependency on illumination conditions.	Effectiveness is dependent on adequate illumination conditions within the borehole. In poorly lit environments, or in situations where natural lighting is insufficient, the quality of the captured images may be compromised, impacting the accuracy of the assessment.

Note: Borehole cameras primarily provide visual information about rock structures and fractures but may not offer feedback on fluid flow dynamics within the borehole. Understanding the movement of fluids, such as water or gas, is crucial for predicting potential hazards and stability issues.



Figure 7—Rock fracturing ahead of a mining face, as observed from mine drill core after destress blasting (Sengani, Zvarivadza, 2018a)

GPR emerges as a non-destructive testing method, allowing for the assessment of rock fracturing without causing any damage to the rockmass. Its real-time imaging capabilities and high resolution provide detailed evaluation of rock fractures and structures, facilitating accurate characterisation. One of its key advantages lies in its versatility, making it applicable in various geological settings and rock types. Studies show that GPR can be used accurately to identify rock fracturing and geological discontinuities in a rockmass, thereby serving as a reliable tool to assess destress blast design effectiveness for deep underground mining. Limitations come to light in conditions characterised by high conductivity or attenuation, hindering its depth penetration capabilities. Challenges in resolution variability based on frequency and geological conditions, also pose complexities in data interpretation. The accuracy of GPR is influenced by surface roughness, affecting the interaction of radar signals with fracture surfaces.

The borehole periscope serves as a valuable alternative, providing direct visual access to the interior of the borehole for real-time observation and assessment of rock conditions. Its detailed

Table 5

Advantages and disadvantages of the drill core observations method

Advantages		Disadvantages	
Aspect	**Description**	**Aspect**	**Description**
Direct sampling of in situ rock	Extracted directly from the mining excavation face, providing a representative and in situ sampling of the rockmass conditions at the targeted location.	Limited spatial coverage.	Drill core samples represent point-specific information, specific information, and their spatial coverage may be limited.The limitation makes it challenging to extrapolate findings to broader areas of the mining face.
High-quality geological information	Offers high-quality geological information, allowing for detailed analysis of rock types, structures, and fracture patterns. This information is crucial for understanding the natural state of the rockmass.	Disruption of rockmass.	The drilling process to collect core samples may disrupt the natural state of the rockmass to some extent. This disturbance could potentially alter the fracture patterns and stress conditions, impacting the accuracy of the assessments.
Quantitative analysis of fractures	Drill core analysis enables quantitative assessments of fractures, including their orientation, density, and size distribution.	Costly and time-intensive.	Drill core sampling is a relatively costly and time-intensive process. The need for drilling equipment, skilled personnel, and subsequent laboratory analysis can contribute to higher operational expenses and time delays.
Structural mapping	Can be used for detailed structural mapping, helping to identify fault zones, bedding planes, and other geological features that may influence rock stability.	Limited real-time data.	Drill core analysis is not a real-time method. The time required for drilling, core extraction, and subsequent analysis may result in delays, making it challenging to obtain immediate information for on-the-spot decision-making.
Integration with geophysical data	Drill core data can be integrated with geophysical data and other subsurface information, providing a comprehensive understanding of the geological conditions. This multidisciplinary approach enhances the accuracy of rock fracturing assessments.	Sampling bias.	Drill core sampling may introduce bias if the selection of drilling locations is not representative of the overall rockmass conditions, Biased sampling can lead to inaccurate assessments of destress blasting effects.
Longitudinal analysis	Allows for longitudinal analysis along the length of the core, providing crucial observations on the variations in rock properties and fractures along the excavation axis. This longitudinal perspective is crucial for understanding the ground conditions dynamics.	Inability to capture dynamic changes.	Drill core samples provide snapshots of the rockmass at specific points in time. They may not capture dynamic changes that occur rapidly, such as the immediate effects of destress blasting or sudden shifts in stress conditions.
Monitoring changes over time	Repeated drill core sampling over time allows for the monitoring of changes in the rockmass, facilitating the tracking of destress blasting effects and assessing the long-term stability of the underground excavation.		

Note: Even though drill core samples can reveal fractures, assessing the redistribution of stress induced by destress blasting is challenging. This requires additional measurements and considerations beyond the scope of traditional core analysis.

inspection capabilities offer high-resolution imaging, enabling a focused examination of potential fracture zones and geological anomalies. Despite its advantages, limitations arise from its dependence on borehole accessibility. In situations where boreholes are sparse or difficult to access, the coverage and applicability of this method may be constrained. The risk of equipment damage or loss also poses challenges, impacting reliability and lifespan.

Drill core observations involve direct sampling of in situ rock from the mining excavation face. This method offers high-quality geological information, allowing for a detailed analysis of rock types, structures, and fracture patterns. Quantitative assessments of fractures, including orientation, density, and size distribution, provide valuable knowledge. Integration with geophysical data enhances the accuracy of rock fracturing assessments. Restrictions come from the disruption caused by the drilling process, potentially altering fracture patterns and stress conditions. The process is also relatively costly and time-intensive, with delays in obtaining real-time data. The spatial coverage of drill core samples is limited, making it challenging to extrapolate findings to broader areas of the mining face.

Each method, despite providing valuable information, comes with its own set of advantages and disadvantages. A critical consideration is the specific context of the underground mining operation. For instance, GPR is lauded for its non-destructive nature and versatility, yet its limitations in certain geological conditions must be acknowledged. Borehole periscope, with its direct visual access, proves advantageous in targeted analysis but faces challenges in accessibility and equipment fragility. Drill core observations offer high-quality geological information but are constrained by their cost, time intensity, and limited spatial coverage.The choice of technique is not a one-size-fits-all decision but depends on the goals, geological conditions, and safety objectives of the mining operation. Combining these methods can offer a more comprehensive understanding of the rockmass, mitigating the limitations of individual techniques. It is crucial to recognise that accurate interpretation of data from these methods requires expertise, and challenges may arise in distinguishing fractures from other geological structures, especially in complex conditions.

The significance of considering environmental factors, such as water content in the rockmass, cannot be overstated. The

performance of these methods, particularly GPR, may be influenced by factors like water saturation, impacting their effectiveness. The issue of electromagnetic interference is also raised, where external sources like power lines can compromise the quality and reliability of data obtained. Such considerations highlight the need for a holistic approach that incorporates not only the technical aspects of these methods but also the external conditions that may affect their performance.It can be noted that the evaluation of rock fracturing ahead of the mining face is a multifaceted task that requires a careful balance between various techniques. The advantages of non-destructive testing, real-time imaging, and high-resolution analysis must be weighed against limitations in depth penetration, resolution variability, and interpretational challenges. The application of these methods should align with the specific goals of the mining operation and the geological context, ensuring a comprehensive and reliable assessment of rockmass conditions.To further assist readers in appreciating the relative strengths and limitations of different rock fracture monitoring methods, a detailed side-by-side technical comparison of ground penetrating radar, borehole periscope inspections, and drill core observations is presented in Table 6.

This structured comparison enables a clearer understanding of how each method complements the others and informs the choice of evaluation techniques in practical deep mining environments.

The comparison clearly shows that no single method is universally superior; rather, each offers distinct technical advantages under different operational conditions. An integrated monitoring approach, taking the advantages of the rapid survey capabilities of GPR, the detailed visualisation offered by borehole periscopes, and the geological richness captured in drill cores, is recommended for achieving a robust, high-confidence assessment of rock fracture networks following destress blasting interventions.

Use of rockburst prediction criteria

Calculation of the energy balance in terms of the strain energy stored in the rockmass and the energy released by the rockmass enables rockburst control practitioners to determine the propensity of the rockmass to burst. In view of destress blasting, the energy balance can be determined before and after destress blasting to evaluate the efficiency of the destress blast design.

Table 6

Comparative technical evaluation of some rock fracture monitoring methods in deep level hardrock mining

Aspect	Ground penetrating radar	Borehole periscope	Drill core observations
Measurement type	Electromagnetic imaging.	Visual inspection through borehole.	Physical rock sample analysis.
Invasiveness	Invasiveness.	Semi-invasive (requires borehole).	Invasive (requires drilling).
Real-time capability	YES.	YES.	No (required processing).
Resolution	High (depends on frequency).	Very high (direct observation).	Very high (physical sample).
Depth penetration	Moderate to high.	Limited to borehole length.	Limited to core length.
Coverage area	Broad (within EM wave penetration limits).	Point-specific.	Point-specific.
Sensitivity to rock properties	High (conductivity affects results).	Low.	Low.
Ability to detect microfractures	Moderate.	High.	Very high.
Environmental influence	High (water, mineralisation affect signals).	Moderate (lighting, borehole quality)	Low.
Equipment portability	Moderate to low.	Moderate.	Low (requires drilling rig).
Data interpretation complexity	High (requires skilled geophysicists/ other experts).	Moderate (geological expertise required).	Moderate to high (geological expertise).
Cost	Moderate to high (depending on system).	Moderate (equipment plus borehole cost).	High (drilling and analysis cost).
Speed of data acquisition	Fast.	Moderate (borehole inspection time).	Slow (drilling, extraction, logging).
Structural mapping capability	Good (large structures better).	Excellent (local fractures).	Excellent (all fractures visible).
Hazard detection	Good (rock discontinuities, voids).	Good (fracture zones).	Excellent (can reveal hidden structures).
Suitability for routine monitoring	Very good.	Good.	Poor (too time-consuming).
Other limitations	Conductivity, resolution variability.	Borehole access needed, damage risk.	Expensive, spatially limited.
Optimal geological conditions	Dry, resistive rocks.	Any rock type (depends on borehole quality).	Any rock type.
Electromagnetic interference	High sensitivity.	None.	None.
Overall strength	Rapid fracture detection over areas.	High resolution, visual fracture details.	High-quality geological and structural data.

From the work of his research team conducted over many years, together with observations from several other expert researchers, Mitri (2022) provided three key rockburst criteria, which can be used to assess the efficiency of destress blasting in deep underground hardrock mining, which are F, BSR, and BPI. Each criterion provides valuable perspectives into the potential for rockmass failure and aids in optimising destress blasting strategies for enhanced safety and efficiency. The technical details and motivation behind the use of F, BSR, and BPI in evaluating destress blasting design performance revolve around their capabilities to quantify energy storage, assess brittleness, and provide a comprehensive index of rockmass properties. These criteria, when integrated and monitored over time, enable practitioners to make informed decisions to prevent or mitigate the risk of rockbursts in underground mining operations through the design of efficient destress blasts. The three are discussed as follows.

Strain energy storage coefficient (F)

The principle of F is premised on the observations of strain energy (area under a stress–strain curve of a rock sample) changes when a rock sample is uniaxially compressed to 80% of its maximum uniaxial compressive strength and the load is released gradually to zero. Since loading the specimen to 0.8UCS makes transition from elastic behaviour to plastic behaviour, permanent damage is experienced by the specimen, leading to strain energy being spent on plastic deformation (represented as W_{sp} (area OAC) in Figure 8). The total strain energy generated in the specimen when it is uniaxially compressed to 0.8UCS is represented as W_{tot} (area OAB in Figure 8). The strain energy stored in the specimen (W_{st}) is the difference between Wtot and W_{sp}. From the work of Kidybinski (1981) and Wang et al. (1998), F is defined as the ratio of W_{st} to W_{sp} and Equations 4 to 7 are used in the formulation of the ratio using Figure 8.

$$W_{tot} = \int_0^{\varepsilon_B} f_1(\varepsilon)d\varepsilon \quad [4]$$

$$W_{st} = \int_{\varepsilon_c}^{\varepsilon_B} f_2(\varepsilon)d\varepsilon \quad [5]$$

$$W_{sp} = W_{tot} - W_{st} \quad [6]$$

$$F = \frac{W_{st}}{W_{sp}} \quad [7]$$

The criterion for judging rockburst intensity based on F is given in Table 7.

F serves as an indicator of the energy that can be released during a rockburst. Higher values of F imply a greater potential for energy release, signalling a higher risk of rockmass failure. Monitoring changes in F before and after destress blasting helps evaluate the effectiveness of the blasting in reducing strain energy storage. A decrease in F indicates successful energy dissipation, contributing to rockburst prevention.

Despite the fact that F provides critically valuable information into the propensity of a rockmass to release stored strain energy during failure, it is important to recognise that the determination of F is sensitive to sampling variability and the inherent differences between laboratory testing conditions and actual in situ field conditions. Sampling variability arises due to the natural heterogeneity of rockmasses. Laboratory specimens are often extracted as relatively small, intact core samples that may not fully represent the large-scale variability found underground. Factors such as mineral composition, grain size distribution, microfracturing, alteration zones, and anisotropy within the rockmass may not be adequately captured in the limited volume of laboratory samples. Laboratory-derived F values might either underestimate or overestimate the energy storage potential of the broader rockmass as a result, depending on whether the sampled cores are stronger or weaker than the average in situ conditions. Laboratory tests typically impose idealised loading conditions, such as uniform uniaxial compression at controlled strain rates, that differ significantly from the complex, multi-axial and time-dependent stress regimes experienced in situ. Stress states are influenced by excavation-induced stress concentrations, seismic wave propagation, and long-term creep behaviour in the field, which are not easily replicated in laboratory environments. Laboratory tests are performed on relatively dry samples, whereas in situ rockmasses may be saturated or partially saturated, further altering their mechanical response and energy storage behaviour.

The transition from laboratory to field conditions therefore introduces uncertainty into the direct application of F values. It is recommended to use a statistically significant number of samples for laboratory testing to mitigate this, capturing a broad spectrum of geological variability. Laboratory-derived F values should ideally be calibrated against observed field behaviour, such as the incidence and severity of rockbursts, microseismic energy release patterns, and measured deformation responses. Integrating F with in situ stress measurements, seismic monitoring, and numerical modelling in high-risk areas enhances the robustness of destress blasting design and rockburst risk assessments. Acknowledging these limitations ensures that the interpretation of F is contextually appropriate, and that risk management strategies based on F are both technically defensible and operationally effective in complex deep mining environments.

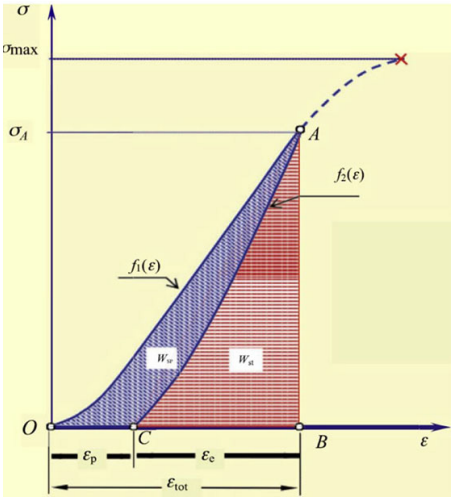


Figure 8—Typical stress-strain curve for uniaxial compression indicating loading and unloading curves (Cai, 2016)

Table 7

Rockburst severity judgement based on strain energy storage coefficient of rocks (Cai, 2016)

F value	Rockburst severity
F ≥ 5	Strong
2 < F < 5	Weak to medium
F ≤ 2	Slight to weak

Table 8

Advantages and disadvantages of using F

Advantages		Disadvantages	
Aspect	**Description**	**Aspect**	**Description**
Quantitative energy assessment	Provides a quantitative assessment of the strain energy stored in the rockmass, allowing for a precise measurement of the potential energy that can be released during a rockburst.	Complexity in calculation.	Calculation of F involves integration of stress-strain curves, which can be complex and may require specialised software or expertise. This complexity may limit its practical application without adequate resources.
Sensitive to rockmass changes	Sensitive to changes in the stress-strain behaviour of the rockmass. Monitoring F enables the detection of alterations in the rockmass' mechanical properties, making it a valuable tool for assessing the impact of destress blasting.	Dependency on rock sample quality.	F calculations are dependent on the quality of rock samples and the representativeness of stress-strain curves. Variabilityin rock sample quality may introduce uncertainties in F values, affecting the reliability of predictions.
Early warning system	Can serve as an early warning system for potential rockbursts. By monitoring changes in F values over time, mining operators can proactively identify areas at risk and implement preventive measures before a rockburst occurs.	Limited spatial coverage.	Values of F are typically calculated based on data from specific rock samples. The spatial coverage of this information may be limited, making it challenging to extrapolate F values to broader areas of the mining excavation face.
Integration with blasting strategies	Values of F can be integrated into the optimisation of destress blasting strategies. Adjustments to blasting parameters can be made based on F values, ensuring that the energy release potential is managed and controlled effectively.	Interpretation challenges.	Interpreting F values may require a deep understanding of rock mechanics. Misinterpretation or insufficient expertise in analysing F values may lead to inaccurate judgments on rockburst severity.
Post-blasting evaluation	F values are instrumental in post-blasting evaluations. A decrease in F indicates successful energy dissipation, providing direct feedback on the performance of destress blasting in reducing the risk of rockbursts.	Limited representation of in situ conditions.	The strain energy stored in a rock sample may not fully represent in situ conditions. The difference between laboratory tests and actual field conditions introduces limitations in applying F values to predict rockbursts accurately.
Clear severity categories	The categorisation of rockburst severity based on F values provides a clear and actionable framework for assessing the potential impact. This categorisation aids in prioritising areas of concern and implementing targeted destress blasting measures.	May not capture short-term changes.	F values may not capture short-term changes in rockmass behaviour. Rapid changes or dynamic conditions occurring shortly after destress blasting may not be adequately reflected in F values.
Benchmarking blasting techniques	F values provide a benchmark for evaluating the effectiveness of different destress blasting techniques. Comparative analysis allows practitioners to optimise destress blasting strategies based on their impact on reducing strain energy storage.	Sensitivity to sample preparation.	Values of F can be sensitive to sample preparation methods. Inconsistencies in sample preparation, such as variations in specimen size or shape, may introduce errors in F calculations, impacting the reliability of predictions.

Note: Rock properties, such as UCS and stress-strain behaviour, can exhibit inherent variability. This variability introduces uncertainties in F calculations, making it challenging to provide precise predictions of rockburst severity for all scenarios.

The advantages and disadvantages of using F for rockburst prediction, and destress blasting design and evaluation are given in Table 8.

Brittle shear ratio (BSR)

Adopting the work of Castro et al. (1997) on rockmass damage initiation, Mitri (2022) explains the application of BSR in hardrock mining to evaluate rockburst potential. The key aspects of the criterion are summarised as follows:

$$BRS = \frac{\sigma_1 - \sigma_3}{UCS} \quad [8]$$

Where:
σ_1 is the major principal stress.
σ_3 is the minor principal stress.
UCS is the uniaxial compressive strength.

The rockburst propensity using the BSR criterion is assessed using potential for strain bursting as shown in Table 9.

Table 9

BSR criterion for the assessment of stain bursting potential (Mitri, 2022 based on Castro et al., 1997)

$\frac{\sigma_1 - \sigma_3}{UCS}$	Rockmass damage	Potential for strain bursting
< 0.35	No to minor	No
0.35 to 0.45	Minor (e.g., surface spalling)	no
0.45 to 0.6	Moderate (e.g., breakout formation)	Minor
0.6 to 0.7	Moderate to major	Moderate
> 0.7	Major	Major

BSR values less than 0.35 suggest no to minor rockmass damage, with no potential for strain bursting. As BSR values increase, the potential for strain bursting escalates, moving from minor to major damage categories. Before destress blasting, BSR can be calculated based on stress conditions and rock properties. This pre-blasting assessment sets a baseline for evaluating the effectiveness of destress blasting in altering the stress state and reducing the potential for brittle failure. After destress blasting, changes in BSR can be monitored. A decrease in BSR indicates a reduction in the potential for brittle failure, suggesting successful stress redistribution and a lowered risk of strain bursting. BSR values guide the optimisation of destress blasting parameters. Adjustments can be made to the blasting design to achieve the desired reduction in BSR, aligning with safety objectives and minimising the risk of rockbursts.

BSR has proven to be an effective indicator for assessing rockburst potential in hardrock mining environments, yet it is critical to acknowledge that its reliability is strongly context-dependent. The BSR calculation fundamentally relies on accurate measurements of the major and minor principal stresses (σ_1 and σ_3) and the uniaxial compressive strength (UCS) of the rockmass. In deep level mining, obtaining precise in situ stress measurements presents considerable challenges due to complex geological structures, variable rockmass properties, and operational constraints. In situ stress fields in deep hardrock mines are often highly heterogeneous in practice, influenced by factors such as lithological layering, faulting, historical mining-induced stress redistributions, and natural anisotropies. Techniques commonly used to measure in situ stresses, such as overcoring, hydraulic fracturing, and borehole slotter methods, are each subject to inherent limitations, measurement errors, and assumptions that may not fully capture the true stress state, especially at great depth (Ljunggren et al., 2003; Gaines et al., 2012; Lin et al., 2018; Li et al., 2024; Li et al., 2025). These uncertainties directly propagate into BSR calculations, affecting the accuracy of the predicted rockburst proneness.

BSR values are also sensitive not only to the absolute magnitudes of principal stresses, but also to the stress ratio between σ_1 and σ_3. Localised stress concentrations, stress shadow effects from nearby excavations, and time-dependent stress changes can all skew the stress measurements, thereby impacting the calculated BSR. Caution must be exercised when interpreting BSR in isolation, particularly in geologically complex or seismically active areas. To enhance the robustness of BSR-based assessments, it is recommended that BSR be used alongside multiple independent data sources. These may include microseismic monitoring data, numerical modelling outputs (e.g., elastic or elastoplastic stress models), mapped fracture orientations, and observational records of rockmass behaviour (e.g., spalling, slabbing, or strainbursting). Sensitivity analyses, considering plausible variations in stress magnitude and orientation, are also vital to quantify the impact of uncertainty on BSR predictions. It can be noted that BSR remains a valuable and practical tool for evaluating brittle failure potential in underground mines, but a clear understanding of its context dependence and sensitivity to in situ stress uncertainties is essential. Integrating BSR assessments with other empirical, observational, and numerical techniques provides a more comprehensive and justifiable approach to managing rockburst hazards in deep mining environments.

Several studies shed more light on the concept of BSR, coverage of which is significant to destress blasting studies. These studies include the following: Rojas-Perez et al., 2024; Shnorhokian, Ahmed, 2024a; Kabwe et al., 2023; Zhang et al., 2023b; Shnorhokian, Mitri, 2022; Vennes, Mitri, 2022; Heidarzadeh et al., 2021; Heidarzadeh et al., 2020; Vennes et al., 2020; Sainoki et al., 2019; Vennes, 2019; Zhou et al., 2018; Shnorhokian et al., 2018; Vennes, Mitri, 2017; Vennes, Mitri, 2016; Sainoki et al., 2016; Shnorhokian et al., 2015; Shnorhokian et al., 2014. The advantages and disadvantages of using BSR for rockburst prediction and destress blasting design and evaluation are presented in Table 10.

Burst potential index (BPI)

The concept of energy balance can be used to evaluate the burst potential of the rockmass as a result of stress redistribution when destress blasting is implemented. This entails manipulation of the energy balance equations to ascertain the amount of energy available to induce rockbursting. Several studies on rockburst prediction based on energy balance evaluation have been done and are crucial to destress blasting design research (Watson et al., 2025; Gao et al., 2024; Zhang et al., 2023b; Luo, Gong, 2023; Askaripour et al., 2022; Li et al., 2022; Papadopoulos, Benardos, 2021; Gao et al., 2020; Khademian, Ozbay, 2019; Zhao et al., 2019; Khademian, Ugur, 2018; Zhou et al., 2018; Hamdi et al., 2017; Mazaira, Konicek, 2015; Qiu et al., 2014; Sirait et al., 2013; Lafont et al., 2013; Konicek et al., 2013; Al Heib et al., 2013; Wattimena et al., 2012; Brady, Brown, 2006; Tang, 2000; Tang, Mitri, 2001; Tajduś et al., 1997; Mitri et al., 1993; Minney, Naismith, 1993; Hedley, 1992; Boldstad, 1990; Salamon, 1984, 1983, 1974,1970; Walsh, 1977; McMahon, 1988; Budavari, 1983; Ivanov et al., 1980; Cook et al., 1966, 1978). The rockburst potential is influenced by excavation geometry and stress changes. Studies by Ortlepp (1983) show that the rockmass behaves elastically in rockburst scenarios. Mitri et al. (1999) note that, due to this elastic behaviour, the energy changes in the rockmass as a result of rock bursting can be modelled using elastic constitutive laws. The use of elastic laws to evaluate the energy available to induce rock bursting is conservative, since the energy used in fracturing the rock is not accounted for, therefore overestimating the energy available to induce rock bursting (Mitri et al., 1999). For practical purposes, Mitri et al. (1999) provide the following formulation (Equation 9), which can be used to evaluate the burst potential of a rockmass due to stress and excavation geometry changes.

$$BPI = \frac{ESR}{e_c} \times 100$$
$$e_c = \frac{1}{2E}\sigma_c^2 \quad [9]$$

Where:
ESR is energy stored in the rock as determined through numerical modelling.
e_c is the critical energy capacity of the rock.
σ_c is uniaxial compressive strength.

Strain bursting is highly likely to occur when the BPI is greater than 100%.

In as much as BPI offers a powerful quantitative method for assessing the propensity of rockmass failure based on the energy balance approach, it is important to recognise that its accuracy is inherently dependent on the reliability of the numerical modelling inputs used to estimate the energy stored in the rockmass (ESR). Uncertainties in critical input parameters, including in situ stress magnitudes and orientations, mechanical properties such as Young's modulus, Poisson's ratio, uniaxial compressive strength

Table 10

Advantages and disadvantages of using BSR

Advantages		Disadvantages	
Aspect	**Description**	**Aspect**	**Description**
Sensitivity to stress conditions	Highly sensitive to stress conditions, providing a responsive indicator of the stress state within the rockmass. This sensitivity enhances the ability to detect changes in rockburst potential.	Dependency on uniaxial compressive strength (UCS).	BSR is dependent on UCS, which can vary across rock types and conditions. This dependency may limit the generalisation of BSR values, particularly when UCS exhibits significant variability.
Quantitative brittle failure assessment	Offers a quantitative measure for assessing brittle failure potential. The numerical values allow for a clear and precise evaluation of the propensity for strain bursting, aiding in decision-making for destress blasting.	Limited to brittle failure assessment.	Primarily assesses brittle failure potential. Although effective for train bursting evaluation, its focus on brittleness may not capture the full spectrum of rockmass behaviour, necessitating the consideration of additional criteria for a comprehensive assessment.
Intuitive severity classification	The categorisation of potential for strain bursting based on BSR values provides an intuitive severity classification. This simplifies the interpretation of results and facilitates effective communication of risk levels to mining personnel.	Influence of laboratory conditions.	BSR calculations may be influenced by laboratory conditions. Differences between laboratory tests and in situ conditions may introduce biases, requiring careful consideration when interpreting BSR values.
Baseline for pre-blasting assessment	Serves as a baseline for pre-blasting assessment. Calculating BSR before destress blasting establishes a reference point, enabling mining personnel to gauge the initial rockburst potential and design appropriate destress blasting strategies.	Limited spatial coverage.	Values of BSR are typically calculated based on specific stress conditions and rock samples. The spatial coverage of this information may be limited, making it challenging to extrapolate BSR values to broader areas of the mining excavation face.
Real-time monitoring capability	BSR can be monitored in real-time, allowing for continuous assessment of rockmass conditions. This capability facilitates timely adjustments to destress blasting plans based on dynamic changes in the geological environment.	Dependency on homogeneous stress conditions.	Calculations of BSR assume relatively homogeneous stress conditions. Variations in stress distribution within the rockmass may lead to inaccuracies in BSR predictions, especially in areas with complex geological structures.
Dynamic optimisation of blasting parameters	Values of BSR guide the dynamic optimisation of destress blasting parameters. Adjustments to blasting design can be made to achieve a desired reduction in BSR, aligning with safety objectives and minimising the risk of rockbursts.	Insensitivity to localised stress concentrations.	BSR calculations may not be sufficiently sensitive to localised stress concentrations. In areas with high-stress gradients or focal stress points, BSR may overlook the potential for localised brittle failure, impacting the precision of rockburst predictions.
Effective communication tool	BSR values can serve as an effective communication tool. The simplicity of the criterion and its clear classification allow for efficient communication of potential risks to stakeholders, fostering a shared understanding of rockburst severity.	Limited integration of microseismic data.	Faces challenges in effectively integrating microseismic data. Microseismic events, indicative of rockmass behaviour, are crucial for understanding dynamic changes. The current limitations in incorporating microseismic data into BSR analyses may hinder a comprehensive assessment of rockburst potential.
Integration with risk management strategies	Can be integrated into broader risk management strategies. Its incorporation into risk assessments allows for a holistic approach to destress blasting design, considering both the immediate reduction in rockburst potential and long-term safety planning.	Sensitivity to rate-dependent rock properties.	May exhibit sensitivity to rate-dependent rock properties. In situations where the rock's behaviour is influenced by loading rates, the static nature of BSR calculations may not fully account for time-dependent variations in strain and stress, potentially affecting the accuracy of predictions.

Note: Like the other discussed methods, BSR calculations typically do not consider the impact of thermal effects on rock properties. In mining operations where temperature variations are significant, the omission of thermal considerations may result in incomplete assessments of rockburst risk.

(UCS), and rockmass anisotropy, can significantly influence the predicted energy accumulation and dissipation within the rockmass. Slight variations in measured UCS or elastic modulus due to sample heterogeneity, scale effects, or laboratory testing variability, as an example, can lead to notable differences in modelled stress fields and therefore the computed ESR values. Geological complexities such as unaccounted for joint sets, faults, or heterogeneous lithological transitions, may not be fully captured in the numerical model, introducing further uncertainties into the energy distribution predictions. Boundary conditions, assumed failure criteria (e.g., Mohr-Coulomb versus Hoek-Brown), and simplifications in material behaviour (linear elasticity versus strain-softening) within the model can introduce systematic biases. These factors can result in either underestimation or overestimation of BPI values, potentially affecting the assessment of burst proneness and leading to either excessive conservatism or overlooked hazards. Recognising these limitations, it is recommended that BPI assessments be supported by careful sensitivity analyses, wherein the impacts of key parameter variations are systematically evaluated. Probabilistic modelling approaches and back-analysis of historical seismic events, where feasible, can also help in refining the input parameters and reducing uncertainty. BPI results, ultimately, should not be interpreted in isolation but rather integrated with complementary observational data, such as microseismic monitoring trends, rock fracture mapping, and field-measured stress changes, to provide a balanced and robust evaluation of rockburst risk following destress blasting. Acknowledging and appropriately managing input uncertainties is critical for ensuring that BPI-based assessments remain a reliable and practical tool for rockburst hazard management in deep level mining operations.

BPI provides a holistic assessment of the rockmass, considering multiple mechanical properties. This comprehensive approach enhances the predictive capability of rockburst potential. Evaluating changes in BPI before and after destress blasting aids in optimising blasting parameters. A decrease in BPI signifies positive modifications in the rockmass properties, indicating successful destress blasting. The advantages and disadvantages of using BPI for rockburst prediction and destress blasting design and evaluation are presented in Table 11.

Table 11

Advantages and disadvantages of using BPI

Advantages		Disadvantages	
Aspect	**Description**	**Aspect**	**Description**
Comprehensive energy balance assessment	Employs the concept of energy balance, offering a comprehensive assessment of the rockmass' burst potential by considering the manipulation of energy balance equations. This holistic approach enhances the understanding of stress redistribution and potential rockburst scenarios.	Limited accounting for fracture energy.	BPI's conservative approach, albeit preventing underestimation, does not account for the energy used in fracturing the rock. This limitation may result in overestimating the energy available to induce rock bursting in certain scenarios.
Consideration of excavation geometry	Takes into account excavation geometry changes, acknowledging the influence of tunnel or mining cavity shapes on the rockmass' burst potential. This consideration adds a practical dimension to the evaluation, aligning with real-world mining scenarios.	Complexity in numerical modelling.	The incorporation of numerical modelling for determining ESR introduces complexity. The reliance on numerical methods may pose challenges in practical applications, requiring specialised expertise and resources for accurate implementation.
Modelling elastic behaviour in rockburst scenarios	The use of elastic constitutive laws, as per Mitri et al. (1999) and Ortlepp (1983), enables the modelling of the rockmass' elastic behaviour during rockburst scenarios. This modelling approach enhances the accuracy of energy change assessments.	Assumption of elastic behaviour in rockburst scenarios.	The assumption of elastic behaviour in rockburst scenarios, as modelled by Mitri et al. (1999) and Ortlepp (1983), may oversimplify the rockmass' actual response. Non-elastic behaviours in certain geological conditions may not be fully captured.
Conservative energy evaluation	BPI's conservative approach, as suggested by Mitri et al. (1999), ensures that energy used in fracturing the rock is not accounted for. This conservatism prevents under-estimation of the energy available to induce rock bursting, contributing to a more robust safety assessment.	Inherent limitations in the energy balance concept.	The energy balance concept, though comprehensive, has inherent limitations in capturing all dynamic interactions within a rockmass. Certain energy-related phenomena during rockburst scenarios may not be fully accounted for in the energy balance equations.
Holistic assessment of rockmass properties	Provides a holistic assessment of the rockmass, considering multiple mechanical properties. This comprehensive evaluation encompasses factors such as energy storage, critical energy capacity, and uniaxial compressive strength, offering a nuanced understanding of the burst potential.	Challenges in field implementation.	Implementing BPI calculations in the field may present challenges. The need for precise numerical modelling and data acquisition may require specialised equipment and expertise, potentially limiting its practicality in certain mining environments.
Numerical modelling for energy storage	BPI incorporates numerical modelling to determine the energy stored in the rock (ESR). This numerical approach enhances precision and reliability in assessing the energy available for inducing rock bursting, contributing to accurate predictive modelling.	Complexities in strain bursting threshold interpretation.	BPI establishes a threshold for strain bursting at values greater than 100% but interpreting the significance of specific BPI ranges in practical terms may present complexities. Clear guidelines for practical decision-making based on BPI thresholds may be lacking.
Practical formulation for burst potential evaluation	Mitri et al. (1999) provide a practical formulation (Equation 14) for evaluating burst potential using BPI. This formula-ion simplifies the application of BPI in practical scenarios, facilitating its adoption adoption in destress blasting design and evaluation.	Varied interpretation of energy storage in rock.	The interpretation of energy storage in rock, as determined through numerical modelling, may vary based on modelling assumptions and methodologies. This variability introduces uncertainties in the reliability of BPI as a consistent burst potential indicator.
Strain bursting threshold for predictive capability	BPI establishes a threshold for strain bursting, indicating high likelihood when BPI is greater than 100%. This threshold provides a clear benchmark for assessing the predictive capability of burst potential, aiding in risk management strategies.	Inability to account for stress relaxation phenomena.	BPI calculations may struggle to account for stress relaxation phenomena over time. Certain rockmasses exhibit stress relaxation behaviour, and BPI's static evaluation may not capture the evolving stress states, impacting the accuracy of burst potential predictions.
Enhanced predictive capability	Consideration of multiple mechanical properties and the energy balance concept contributes to an enhanced predictive capability for rockburst potential. This improvement aids in proactive safety measures and strategic destress blasting planning.	Insensitivity to dynamic rockmass changes.	Calculations for BPI may be insensitive to dynamic changes within the rockmass during mining operations. Rapid alterations in stress distribution or structural changes may not be adequately reflected in BPI values, affecting the criterion's reliability.
Flexible application across various geological conditions	The incorporation of BPI in multiple studies, as highlighted in this section, demonstrates its applicability across various geological conditions. This flexibility ensures its relevance in diverse mining environments.	Limited Integrationof microseismicity data.	Effectively integrating microseismicity data in BPI calculations may be challenging. Microseismic events, indicative of rockmass behaviour may not be fully considered in BPI formulations potentially limiting its sensitivity to subtle changes in rock conditions.

Note: Similar to BSR, BPI may exhibit sensitivity to rate-dependent rock properties. The criterion may face challenges in accurately representing scenarios where the rock's behaviour is influenced by loading rates, impacting burst potential predictions

Key insights on evaluating destress blasting performance using rock burst prediction criteria

Rockburst prediction criteria can be handy in the design of efficient destress blasting. Some of the key rockburst prediction criteria applicable to hardrock mining, as presented by Mitri (2022), are F, BSR, and BPI. The energy balance method is pivotal in the assessment of the burst potential of underground mining excavations. It involves assessing the strain energy stored in the rockmass against the energy released, aiding in the determination of rockmass propensity to burst. The three criteria presented by Mitri (2022) are derived from this method, offering a holistic approach to evaluating destress blasting efficiency. Selected practical examples from deep mining operations are integrated in this discussion to further illustrate the applicability of these criteria in evaluating destress blasting performance.

F is a crucial indicator representing the ratio of strain energy stored to that spent on plastic deformation during uniaxial compression. High F values suggest a greater potential for energy release, signifying a higher risk of rockmass failure. Monitoring F changes post-destress blasting aids in assessing its effectiveness. The advantages include quantitative energy assessment, sensitivity to rockmass changes, and serving as an early warning system. Challenges arise from its complexity of calculation, dependency on sample quality, and limited spatial coverage.

In the Sanshandao gold mine case study conducted by Cai (2016), F was applied to evaluate five rock types, resulting in the classification of four rock types as having strong rockburst potential and one as medium. The findings aligned with other indices (e.g., brittleness coefficient, burst energy coefficient), confirming the high rockburst risk of the mine and, showing that F serves as a predictive tool, enabling proactive rockburst prevention in deep mining operations (Cai, 2016). Targeted destress blasting can successfully reduce F values in rockburst prone zones, and subsequent operational records can confirm this by showing a marked decline in burst events to validate F as a practical tool for pre- and post-blasting evaluation.

Rockburst potential is assessed by BSR based on the ratio of major to minor principal stress over the uniaxial compressive strength. It categorises potential for strain bursting from 'no' to 'major.' BSR proves sensitive to stress conditions, allowing real-time monitoring and dynamic optimisation of blasting parameters. Its challenges involve dependency on UCS, limited spatial coverage, and potential oversimplification of rockmass behaviour. Vennes et al. (2020) employed the BSR technique (creating fractured panels to dissipate stress in ore pillars, reducing local stiffness and stress concentrations) to evaluate the effectiveness of large-scale destress blasting for their case study of the Copper Cliff mine. Numerical modelling, validated by field stress measurements, showed that destress blasting lowered BSR values in targeted zones. In one stope, they noted that BSR decreased from 0.93 to 0.87 after blasting, reducing the volume of high-risk ore (BSR > 0.7) from 15% to 7.7% (Vennes et al., 2020). The practical application of BSR lies in guiding blast design and mining sequences. Mining practitioners can optimise destress blasting parameters (e.g., explosive energy, panel geometry) by monitoring BSR changes to ensure stress relief and safer extraction. The study by Vennes et al. (2020) confirmed that BSR, combined with other indices like the BPI, provides a reliable framework for rockburst risk management in deep, high-stress mining environments.

BPI evaluates burst potential by considering energy storage, excavation geometry, and rock properties. It provides a comprehensive assessment, incorporating multiple mechanical properties. Decreases in BPI post-destress blasting indicate positive modifications in rockmass properties. Advantages include a holistic evaluation and consideration of excavation geometry, while challenges include complexity in numerical modelling, potential conservatism, and difficulties in field implementation. One effective application of the BPI is demonstrated in the study by Xu et al. (2022), which evaluates rockburst tendencies in the context of sill pillar recovery strategies using finite element modelling. They reveal that the assessment of tangential stress, alongside the BPI, provides more clarity into the stability of stope accesses during recovery operations, thereby facilitating safe mining practices. Verma et al. (2024) propose an energy-based strain burst criterion that integrates stress conditions and material characteristics. They introduce a 'Burst Envelope' concept, which aids in understanding localised failure mechanisms, and develop a scalar burst index that quantifies burst potential. This approach underscores the significance of material properties and stress conditions in predicting rockburst events. Numerical simulations based on mining-induced stress redistribution can predict BPI values exceeding 100% in mining areas. Controlled destress blasts can be strategically deployed together with monitoring BPI values to decrease the BPI values below critical threshold. This intervention holds great potential to directly mitigate the risk of large-scale violent failures in high-extraction stopes and can demonstrate the operational value of BPI in guiding destress strategies.

The three criteria offer a comprehensive toolkit for assessing rockburst potential. F, BSR, and BPI, even alongside their advantages, share common challenges such as sensitivity to sample quality, limited spatial coverage, and the need for expertise in interpretation. It can be noted that a holistic approach, combining multiple criteria for a more robust assessment, is of significant importance. The practical application of these criteria in real-world mining scenarios is notable. Each criterion provides evaluation, yet the interplay between them and their integration into broader risk management strategies is crucial. Practical challenges, such as the complexity of calculations and limitations in field implementation, need to be addressed for effective use. The practical examples highlighted in this study collectively underline that rockburst prediction criteria such as F, BSR, and BPI are not just theoretical tools; they have proven, tangible application in real mining scenarios. Integrating these indices into routine mining practice, alongside numerical modelling and seismic monitoring, provides a powerful, validated methodology for optimising destress blasting and improving underground mine safety.

The extensive list of studies cited highlights the depth of research in this field. It also points to potential gaps, such as the limited integration of microseismic data and challenges in representing dynamic rockmass changes. Future research could focus on refining these criteria and addressing the evolving needs of mining operations. The rockburst prediction criteria offer a nuanced approach to destress blasting design. Recognising their challenges, their potential in enhancing safety and efficiency in underground mining operations is evident. A collaborative effort in further research and practical implementation is crucial for refining these criteria and ensuring their effectiveness in diverse geological conditions.

Seismic monitoring

Mining-induced seismic events can be monitored using seismic monitoring systems, enabling mining personnel to forecast

rockburst hazards and effectively manage them (Durrheim, 2025; Rapetsoa et al., 2025; Wu et al., 2024; Zhang et al., 2023a; Li et al., 2023; Fuławka et al., 2022a; Fuławka et al., 2022b; Zhao et al., 2022; Feng et al., 2022; Wang et al., 2022; Wang et al., 2021; Zhang et al., 2021; Vennes et al., 2020; Rahimi et al., 2020, Ma et al., 2020; Dahnér, Dineva, 2020; Simser, 2019; De Santis et al., 2019; Wesseloo, 2018; Ma et al., 2018; Konicek, Waclawik, 2018; Brown, Hudyma, 2018, He et al., 2017; Sainoki et al., 2017; Sengani, Zvarivadza, 2017; Zhang et al., 2017; Glazer, 2016; Mendecki, Malovichko, 2010; Hudyma, Potvin, 2010; Durrheim, 2010; Hudyma, Brummer, 2007; Hudyma, Potvin, 2004; Blake, Hedley, 2003; Beck, Brady, 2002; Potvin, Hudyma, 2001; Duplancic, Brady, 1999; Mendecki, 1996; Hasegawa et al., 1989, among many others). Figure 9 and Figure 10 illustrate the distribution of micro seismic events before and after implementing destress blasting respectively for a deep underground hardrock mine.

It is evident from field observations that destress blasting is accompanied by significantly reduced seismic events at a local scale of the mine. A properly functional seismic monitoring system is a practical and handy tool to observe destress blasting efficiency. Noting the significant value of seismic monitoring, Simser (2019) argues that: *A modern deep hardrock mine arguably should not operate without a seismic monitoring system*. Simser's (2019) assertion is fundamentally accurate, still, it is important to provide a balanced discussion by acknowledging practical considerations such as costs, system limitations, and data resolution challenges. Seismic monitoring systems are invaluable for detecting stress redistribution, locating seismic sources, and tracking precursors to dynamic failures, thereby enabling proactive rockburst management. The installation, operation, and maintenance of high-quality seismic arrays, however, entail significant financial investment. Costs include not only the initial purchase of

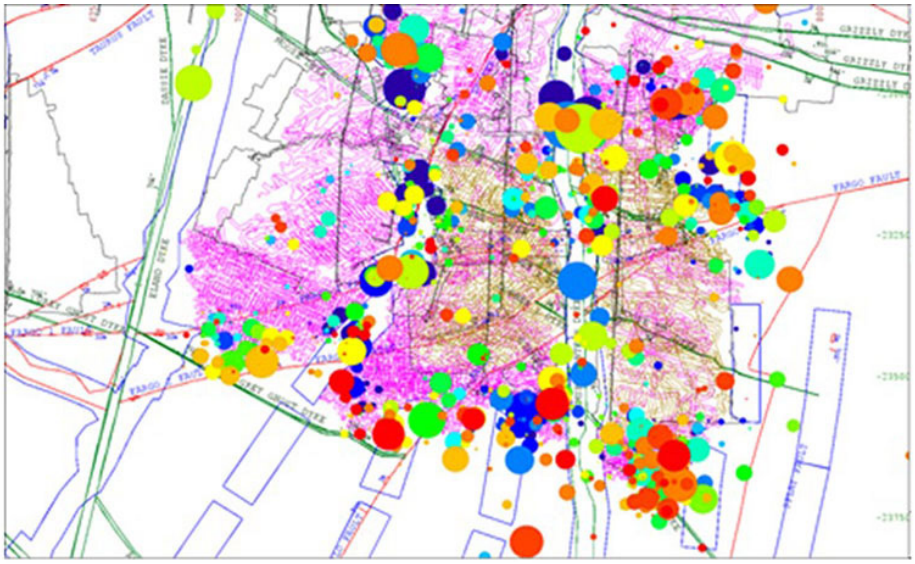


Figure 9—Seismic events before implementation of destress blasting (Sengani, Zvarivadza, 2017)

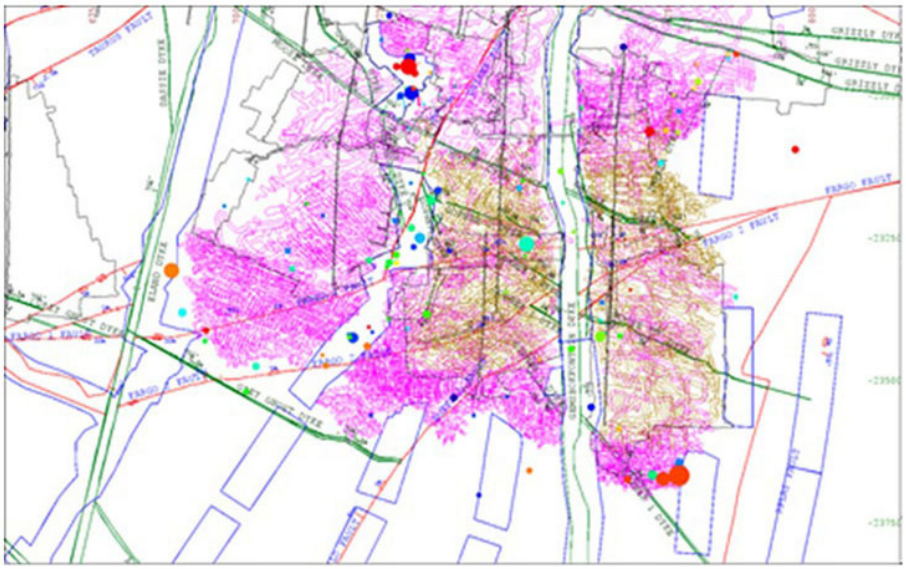


Figure 10—Seismic events after the implementation of destress blasting (Sengani, Zvarivadza, 2017)

geophones, accelerometers, and associated hardware, but also the ongoing requirements for data processing infrastructure, specialist staff, calibration, and periodic system upgrades to maintain sensitivity and reliability. The spatial resolution and sensitivity of seismic monitoring systems are also inherently limited by the number and placement of sensors. Insufficient sensor density can result in large uncertainties in event localisation, magnitude estimation, and focal mechanism analysis, particularly in complex geological environments where wave propagation is heterogeneous. On top of that, distinguishing between mining-induced seismicity and background microseismic noise often demands sophisticated signal processing techniques and expert interpretation, increasing operational complexity. Technological advances such as micro electro mechanical system (MEMS) based accelerometers and machine learning enhanced data interpretation are improving capabilities, but challenges persist, especially for detecting low-energy microseismic events critical for early warning. It can be noted from this that, although seismic monitoring is imperative for deep level mines, a well refined perspective recognises that its deployment must be optimised relative to mine-specific risk profiles, operational budgets, and geotechnical conditions. A tiered approach is recommended: critical areas of the mine may warrant dense, high-resolution monitoring, while less active zones could be covered with lower-density arrays, ensuring effective, risk-prioritised seismic hazard management without excessive financial burden. Amid the clear value of seismic monitoring for managing rockburst risk and evaluating destress blasting effectiveness, it is equally important to critically consider the limitations of seismic systems, their complementary role alongside other monitoring techniques, and practical evidence of their integrated application in deep mining operations.

Limitations, complementary value, and practical evidence of seismic monitoring

Seismic monitoring plays a critical role in managing rockburst risks and evaluating the effectiveness of destress blasting in deep level hardrock mining. Seismic systems provide vital real-time feedback into stress redistribution and dynamic failure mechanisms; there are, however, practical limitations that must be acknowledged when implementing these systems. Spatial resolution and event detection thresholds pose significant challenges. The ability of a seismic system to accurately locate and characterise events is heavily dependent on the number, sensitivity, and strategic placement of sensors. Sparse networks can result in large location uncertainties, misinterpretation of source mechanisms, and failure to detect small, but important, microseismic precursors (Mendecki, 1996; Hudyma, Potvin, 2004; Peng et al., 2020; Barthwal, Van der Baan, 2020). Hidayat et al. (2021) discuss the importance of hypocenter relocation to minimise uncertainties in microseismic activity identification, which is crucial for ensuring the safety of mining operations under complex geological conditions. High-frequency, low-energy microseismic events, which often precede larger rockbursts, may go undetected if sensor sensitivity or density is insufficient. Environmental and operational noise in an active mine, caused by drilling, blasting, equipment operation, and ventilation, can mask true seismic signals. Discriminating between mining-induced seismicity and background noise demands sophisticated signal processing and experienced interpretation, increasing operational complexity (Wesseloo, 2018).

Financial costs present another constraint. Seismic monitoring systems require substantial investment for high-quality sensors, cabling, data acquisition systems, and ongoing maintenance. Additional costs are associated with data analysis expertise, either internally trained or outsourced (Durrheim, 2010). Mines must balance the cost of the system against the potential risk reduction benefit it provides. Another limitation lies in data interpretation complexity. Even with real-time monitoring, understanding the implications of seismic trends requires integration with geological models, mining sequences, and stress analysis. Standalone seismic data, without correlation to other monitoring data, may lead to incomplete or misleading conclusions regarding rockmass stability. Despite these limitations, seismic monitoring complements other rock engineering techniques effectively. When combined with numerical modelling, seismic monitoring validates model predictions of stress redistribution, allowing dynamic updating of rockburst risk maps (Ma et al., 2020). Ground penetrating radar and borehole periscope inspections provide direct imaging of fracture development, which can be correlated with microseismic event clustering zones, enhancing fracture network interpretation. Drill core analysis, in a similar approach, provides physical verification of fracture patterns predicted by seismicity patterns, strengthening confidence in rockmass behaviour models.

Practical evidence of the value of integrated seismic monitoring exists. Simser (2019) reports on Canadian hardrock mines that implemented comprehensive seismic monitoring systems integrated with numerical modelling to manage rockburst risks during deep mining. *Seismic monitoring remains one of the best tools for estimating rockburst risk*, asserts Simser (2019) from his practical observations from the Canadian hardrock mines. For effective large-scale destress blasting campaigns, seismic data can reveal spatial migration of seismicity away from production areas. Seismic moment tensor analysis correlation with fracture orientations observations through borehole logging can provide strong validation of the combined monitoring approach. In the deep gold mines of South Africa, seismic systems have been used in conjunction with visual geological mapping and borehole imaging to predict and manage strainbursts in high-risk panels, notably improving safety performance (Durrheim, 2010; Sengani, Zvarivadza, 2017; Sengani, 2020a). Seismic monitoring systems have practical limitations related to resolution, noise sensitivity, cost, and interpretation complexity, but they are indispensable for effective rockburst risk management. Their power lies not in standalone deployment but in strategic integration with other monitoring and modelling techniques, providing a holistic, dynamic understanding of the evolving rockmass response to mining activities. Future advancements in real-time data fusion, machine learning event classification, and integration with energy-based rockburst prediction models are expected to further enhance the role of seismic monitoring in modern deep level mining.

Innovative destress blasting evaluation methods incorporating geostatistics, machine learning, and IIoT real-time monitoring

Employing geostatistical methods like kriging or conditional simulation could strongly quantify spatial uncertainty and enhance the reliability of blast performance predictions. Geostatistics could help optimise the placement and configuration of destress blast holes by precisely modelling rockmass heterogeneity and identifying areas with higher probabilities of rockburst occurrences. Zvarivadza (2023) covers key concepts on the application of geostatistical methods in the evaluation of destress blasting efficiency.

Incorporation of machine learning techniques could significantly advance the predictive capabilities of the destress blasting evaluation framework. Given the complex, multivariate nature of the data involved, ranging from rock mechanics parameters, seismic data, fracture network imaging, and geomechanical modelling outputs, machine learning approaches such as random forests, gradient boosting, or neural networks could efficiently handle non-linear interactions and provide predictive perspectives with higher accuracy. Machine learning models could also dynamically adapt to incoming data, continually refining destress blasting strategies based on historical outcomes, thereby promoting proactive management of rockburst risks.

Integrating Industrial IoT based real-time monitoring systems, could further enhance data quality and operational responsiveness (Zvarivadza et al., 2024). Deploying sensor networks that continuously capture seismic, deformation, and environmental data in real-time could markedly improve the temporal resolution and accuracy of the evaluation. Such real-time data streams, combined with advanced analytics and cloud-based visualisation platforms, would allow immediate detection and response to stress changes and rockmass behaviour. This integration could substantially elevate the operational reliability of destress blasting, transitioning from retrospective assessments to real-time, data-driven decision-making frameworks. Table 12 presents some innovative destress blasting evaluation methods incorporating geostatistics, machine learning, and IIoT real-time monitoring.

The integration of geostatistical methods, machine learning models, and real-time IIoT monitoring frameworks significantly broadens the traditional destress blasting evaluation approach, offering a multi-dimensional, data-driven, and adaptive strategy that enhances both scientific rigour and operational resilience in deep underground hardrock mining environments.

Conclusions

Practically reliable evaluation of destress blasting is vitally important for developing a reliable destress blasting strategy. This study advances the evaluation of destress blasting by moving beyond traditional descriptive summaries and providing a structured, integrated framework that critically addresses key gaps in current practice. Previous research has highlighted the importance of destress blasting in mitigating seismic hazards in deep hardrock mining. Our work systematically tailors global best practices to the unique geological and operational challenges of deep Swedish mines. The study proposes refinements better suited for Sweden's deep hardrock mining environments by critically reviewing numerical modelling approaches and highlighting their limitations, such as oversimplification of damage zones and the need for anisotropic, time-dependent models. The integration of field-based fracture monitoring methods (GPR, borehole periscope imaging, and drill core observations) with predictive numerical simulations provides a notable, multi-modal evaluation framework. This study also reflects on the combined application of rockburst prediction criteria (F, BSR, BPI) as essential quantitative tools for assessing stress relief effectiveness pre- and post-destress blasting, offering a more robust and risk-informed evaluation process. It is also important to note that this work considers the incorporation of emerging technologies, such as geostatistical simulations to characterise spatial variability, machine learning to predict blast outcomes dynamically, and Industrial IoT-based real-time monitoring to move evaluation from retrospective assessments to predictive, adaptive control.

The new insights gained include:

- Emphasising the critical role of uncertainty quantification in blast performance prediction.
- Highlighting the importance of integrating low-magnitude seismic responses into adaptive destress blasting optimisation.
- Proposing an operational pathway for real-time feedback loops linking monitoring data to model recalibration during ongoing mining.

The proposed framework practically enables mining practitioners to design destress blasting strategies that are site-specific, dynamically adaptable, and scientifically grounded. This can improve operational safety, reduce unplanned seismic disruptions, and optimise drilling and blasting costs for the mining industry. From an academic perspective, the study contributes a refined evaluation methodology that future researchers can extend, particularly by combining energy-based rockburst prediction models with real-time data streams. Future research should focus on validating the proposed framework through field trials in deep Swedish mines, refining machine learning predictive models with larger datasets, and developing standardised protocols for real-time blast effectiveness evaluation based on integrated multi-sensor data. Our study lays the groundwork for a more rigorous, predictive, and operationally impactful approach to destress blasting evaluation in deep hardrock mining environments. It bridges the gap between theoretical destress blasting models and practical deep mining realities, offering a predictive, adaptable framework that strengthens both scientific understanding and field-based application in high-stress mining environments.

Acknowledgements

The authors gratefully acknowledge the financial support from the Strategic Innovation Programme for the Swedish Mining and Metal Producing Industry (STRIM), which is a joint investment from VINNOVA (The Swedish Governmental Agency for Innovation Systems), the Swedish Energy Agency, and Formas, with an additional in-kind contribution from Zinkgruvan Mining AB, LKAB, and Boliden (Ref. No.: 2020-04459).

References

Al Heib, M., Lafont, G., Didier, C., Gunzburger, Y., Piguet, J.P., Pytel, W., Mitri, H. 2013. Critical energy and mine rockburst potential. *ISRM International Symposium-EUROCK*, October 2013. OnePetro.

An, H., Mu, X. 2025. Contributions to Rock Fracture Induced by High Ground Stress in Deep Mining: A Review. *Rock Mechanics and Rock Engineering*, vol. 58, no. 1, pp. 463–511.

Andrieux, P., Hadjigeorgiou, J. 2008. The destressability index methodology for the assessment of the likelihood of success of a large-scale confined destress blast in an underground mine pillar. *International Journal of Rock Mechanics and Mining Sciences*, vol. 45(, no. 3, pp.407–421.

Andrieux, P.P., Brummer, R.K., Liu, Q., Simser, B.P., Mortazavi, A. 2003. Large-scale panel destress blast at Brunswick mine. *CIM Bulletin*, pp. 78–87.

Askaripour, M., Saeidi, A., Rouleau, A., Mercier-Langevin, P. 2022. Rockburst in underground excavations: A review of mechanism, classification, and prediction methods. *Underground Space*, vol. 7, no. 4, pp. 577–607.

Table 12
Some innovative destress blasting evaluation methods incorporating geostatistics, machine learning, and IIoT real-time monitoring

Evaluation method	Description	Technical contribution to destress blasting evaluation
Geostatistical methods		
Ordinary kriging	Interpolation technique assuming spatial correlation between samples.	Predicts stress and rockmass variability spatially, improving blast design precision.
Indicator kriging	Geostatistical method for categorical data (e.g., fractured vs. intact zones).	Maps fracture probabilities, guiding borehole placement.
Co-kriging	Uses secondary variables (e.g., GPR signals) to improve primary stress or fracture data predictions.	Enhances destress target definition with multisource data fusion.
Conditional simulation	Generates multiple equally probable realisations of rockmass properties.	Quantifies spatial uncertainty in blast design outcomes.
Variogram analysis	Statistical tool to describe spatial variability of geological properties.	Enables understanding of fracture and stress anisotropy.
Sequential Gaussian simulation	Stochastic geostatistical method to model continuous variables like rock strength.	Supports probabilistic blast hole positioning optimisation.
Multiple point geostatistics (MPS)	Models complex geological patterns based on training images.	Allows realistic simulation of fracture networks affecting blast efficiency.
Kriging with external drift (KED).	Incorporates external trends (e.g., mining depth) into kriging interpolation.	Improves predictive models of stress fields around excavation fronts.
Uncertainty quantification (UQ) in geostatistics	Measures prediction uncertainty of stress and rockmass conditions.	Guides risk-aware destress blasting design.
Rockmass classification mapping via geostatistics	Combines geostatistics with core logging to produce 3D classification models.	Enables better localisation of preconditioning zones.
Machine learning techniques		
Random forests datasets.	Ensemble learning technique based on decision trees.	Predicts optimal blast parameters using large multivariate
Gradient boosted machines (GBMs)	Advanced tree-based algorithm minimising prediction error sequentially .	Accurately predicts destress blast outcomes using complex, non-linear interactions.
Artificial neural networks (ANN)	Models complex, non-linear relationships between input and output variables.	Learns effective destress blasting patterns from historical blasting-seismicity data.
Support vector machines (SVM)	Classifier/regressor used to model stress conditions leading to successful blasting.	Classifies high-risk areas vs. low-risk zones pre- and post-destress.
Deep learning (DL) models	Advanced neural networks for large-scale data mining.	Detects hidden patterns in seismic and geotechnical time-series data.
Reinforcement learning	Learns optimal blasting strategies by trial and error.	Continuously improves destress blasting planning in dynamic conditions.
Feature engineering from seismic and GPR data	Pre-processing to enhance ML model input quality.	Extracts key patterns improving model accuracy and interpretability.
Ensemble learning	Combines outputs of multiple ML models to enhance robustness.	Reduces predictive uncertainty in blast efficiency forecasts.
Data augmentation for rare events	Synthetic data generation to handle sparse severe event datasets.	Improves ML training for low-frequency rockburst prediction after destress blasting.
Predictive maintenance models for sensors	ML predicting sensor health status.	Increases reliability of real-time IIoT systems during destress blasting.
Industrial IoT (IIoT) real-time monitoring		
Wireless sensor networks (WSN)	Deploys distributed nodes for stress, deformation, and microseismic monitoring.	Enables high-density, real-time monitoring of rockmass behaviour during blasting.
Real-time microseismic monitoring platforms	IoT-connected seismic systems for instant event detection.	Provides immediate feedback on destress blast effectiveness.
Fiber optic sensing (distributed acoustic sensing)	Captures strain and acoustic signals continuously.	Detects fracture growth and stress changes during and after blasting.
Wireless accelerometer arrays	Networks of vibration sensors installed in tunnels and boreholes.	Captures blast-induced stress redistribution in real-time.
Cloud based data integration platforms	Collects, processes, and visualises real-time monitoring data.	Facilitates real-time decision-making post-destress blasting.
Predictive analytics dashboards	Web-based visualisation integrating GPR, seismic, and stress data.	Provides mining practitioners with actionable insights during operations.
Automated alert systems for stress anomalies	Triggers alarms when stress or seismic thresholds are exceeded.	Improves safety by rapid response to unstable conditions.
IIoT enhanced drill and blast scheduling	Adjusts drill and blast plans dynamically based on real-time rockmass data.	Optimises blast timing and location to maximise destressing effect.
Data fusion of seismic, environmental, and deformation sensors	Merges multiple data streams.	Achieves a holistic understanding of blast impacts on mine stability.
Edge computing for on site data processing	Processes sensor data locally at the mine before cloud transmission.	Reduces latency and improves responsiveness of blasting evaluations.

Baranowski, P., Damaziak, K., Mazurkiewicz, Ł., Mertuszka, P., Pytel, W., Małachowski, J., Pałac-Walko, B., Jones, T. 2019. Destress blasting of rockmass: multiscale modelling and simulation. *Shock and Vibration*, 2019.

Barthwal, H., Van der Baan, M. 2020. Microseismicity observed in an underground mine: Source mechanisms and possible causes. *Geomechanics for Energy and the Environment*, vol. 22, p. 100167.

Beck, D.A., Brady, B.H.G. 2002. Evaluation and application of controlling parameters for seismic events in hardrock mines. *International Journal of Rock Mechanics and Mining Sciences*, vol. 39, no. 5, pp. 633–642.

Blake, W. 1972. Destressing test at the Galena Mine. In Transaction of SME-AIME. pp. 294–299. As cited in Sainoki, A., Emad, M.Z. and Mitri, H.S., 2017. Study on the efficiency of destress blasting in deep mine drift development. *Canadian Geotechnical Journal*, vol. 54, no. 4, pp. 518–528.

Blake, W., Hedley, D.G. 2003. *Rockbursts: case studies from North American hardrock mines*. SME.

Bolstad, D.D. 1990. Rockburst control research by the US Bureau of Mines. *Rockbursts and Seismicity in Mines*, pp. 371–375.

Borg, T. 1988. *Ortdrivning med avlastningssprängning; Bergmekanisk uppföljning på 815m nivån i Malmberget*. Report BeFo 331:1/88, SveDeFo 1989:1 (In Swedish).

Brady, B.H., Brown, E.T. 2006. *Rock mechanics: for underground mining*. Springer science & business media.

Brown, L.G., Hudyma, M.R. 2018. Mining-induced seismicity in Canada: a 2017 update. *52nd US Rock Mechanics/Geomechanics Symposium*, June 2018. OnePetro.

Budavari, S. 1983. Response of the rockmass to excavations underground. Rock Mechanics in Mining Practice. *The South African Institute of Mining and Metallurgy Monograph Series M*, 5, pp. 55–76.

Cai, M. 2016. Prediction and prevention of rockburst in metal mines–A case study of Sanshandao gold mine. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 8, no. 2, pp. 204–211.

Cai, M. 2024. Rockburst risk control and mitigation in deep mining. *Deep Resources Engineering*, vol. 1, no. 2, p. 100019.

Castro, L.A., Grabinsky, M.W., McCreath, D.R. 1997. Damage initiation through extension fracturing in a moderately jointed brittle rockmass. *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, no. 3-4, pp. 110-e1.

Chufo, R.L., Johnson, W.J. 1993. A radar coal thickness sensor. *IEEE Transactions on Industry Applications*, vol. 29, no. 5, pp.834–840.

Cook, N.G.W., Fenton, C.T., Lancaster, F.H., More-O'Ferall, R.C., Nienaber, W.C., Van Schalkwijk, A.J.H., Steijn, R.P.G., Tyser, J.A., Wagner, H., Waterman, D.D. 1978. An industry guide to the amelioration of hazards of rockbursts and rockfalls. *Chamber of Mines of South Africa*.

Cullen, M. 1988. Studies of destress blasting at Campbell Red Lake mine. *MSc Thesis*. McGill University, Montreal, Canada.

Dahnér, C., Dineva, S. 2020. Small-scale variations in mining-induced stresses, monitored in a seismically active underground mine. *Proceedings of the Second International Conference on Underground Mining Technology*, November 2020, pp. 233–246. Perth: Australian Centre for Geomechanics.

Dang, L., Yang, H., Teng, B. 2018. Detection imaging of impulse borehole well-logging radar. *EURASIP Journal on Image and Video Processing*, 2018, pp. 1–14.

Daniels, D.J. 1980. Short pulse radar for stratified lossy dielectric layer measurement. *IEE Proceedings F-Communications, Radar and Signal Processing*, vol. 5, no. 127, pp. 384–388).

De Santis, F., Conin, M., Renaud, V., Bernard, P., Dineva, S. 2019. Seismic and aseismic rockmass deformation induced by underground excavations: in-situ monitoring and 3D-numerical modeling in a deep mine.

Drover, C., Villaescusa, E. 2019. A comparison of seismic response to conventional and face destress blasting during deep tunnel development. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 5, pp. 965–978.

Drover, C., Villaescusa, E., Onederra, I. 2018. Face destressing blast design for hardrock tunnelling at great depth. *Tunnelling and Underground Space Technology*, vol. 80, pp. 257–268.

Duplancic, P., Brady, B.H. 1999. August. Characterisation of caving mechanisms by analysis of seismicity and rock stress. *9th ISRM Congress*. OnePetro.

Durrheim, R.J. 2010. Mitigating the risk of rockbursts in the deep hardrock mines of South Africa: 100 years of research. Extracting the science: *A century of mining research*, pp. 156–171.

Durrheim, R.J. 2025. Seismic activity related to mining. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 125, no. 1, pp. iv–iv.

Ellerbruch, D.A., Belsher, D.R. 1978. Electromagnetic technique of measuring coal layer thickness. *IEEE Transactions on Geoscience Electronics*, vol. 16, no. 2, pp. 126–133.

Fedorova, L.L., Savvin, D.V., Fedorov, M.P., Struchkov, A.S. 2016. GPR monitoring of cryogenic processes in subgrade soils. *2016 16th International Conference on Ground penetrating radar (GPR)*. IEEE, Hong Kong, pp. 1–5.

Feng, G.L., Chen, B.R., Xiao, Y.X., Jiang, Q., Li, P.X., Zheng, H., Zhang, W. 2022. Microseismic characteristics of rockburst development in deep TBM tunnels with alternating soft–hard strata and application to rockburst warning: A case study of the Neelum–Jhelum hydropower project. *Tunnelling and Underground Space Technology*, vol. 122, p. 104398.

Fuławka, K., Mertuszka, P., Pytel, W., Szumny, M., Jones, T. 2022a. Seismic evaluation of the destress blasting efficiency. *Journal of Rock Mechanics and Geotechnical Engineering*.

Fuławka, K., Mertuszka, P., Szumny, M., Stolecki, L., Szczerbiński, K. 2022b. Application of MEMS-Based Accelerometers for Near-Field Monitoring of Blasting-Induced Seismicity. *Minerals*, vol. 12, no. 5, p. 533.

Gaines, S., Diederichs, M.S., Hutchinson, D.J. 2012. Review of borehole in-situ stress measurement techniques for various ground conditions and numerical stress estimation considerations. *ARMA US Rock Mechanics/Geomechanics Symposium*, June 2012, pp. ARMA–2012. ARMA.

Gao, H., Xie, H., Zhang, Z., Lu, J., Zhang, D., Zhang, R., Wu, M. 2024. True triaxial energy evolution characteristics and failure mechanism of deep rock subjected to mining-induced stress. *International Journal of Rock Mechanics and Mining Sciences*, vol. 176, p. 105724.

Gao, L., Gao, F., Xing, Y., Zhang, Z. 2020. An energy preservation index for evaluating the rockburst potential based on energy evolution. *Energies*, vol. 13, no. 14, p. 3636.

Glazer, S.N. 2016. Applications of seismic monitoring in combating rock burst hazard. Mine Seismology: *Data Analysis and Interpretation: Palabora Mine Caving Process as Revealed by Induced Seismicity*, pp. 9–29.

Grodner, M. 2001. Delineation of rockburst fractures with ground penetrating radar in the Witwatersrand Basin, South Africa. *International Journal of Rock Mechanics and Mining Sciences*, vol. 38, no. 6, pp. 885–891.

Hainsworth, D.W., McPhee, R.J., Ralston, J.C. 1999. Longwall horizon control (ACARP project C4018): *CSIRO Exploration and Mining Report 658F*. Kenmore, QLD, Australia.

Hamdi, J., Souley, M., Scholtès, L., Al Heib, M., Gunzburger, Y. 2017. Assessment of the energy balance of rockmasses through discrete element modelling. *Procedia engineering*, vol. 191, pp. 442–450.

Hao, L.S., Xu, X.L., Peng S.P., Feng, Y. 2016. Development and application of a novel combined low-frequency antenna for ultra deep advanced detection in mine. *2016 16th International Conference on Ground Penetrating Radar (GPR)*, Hong Kong, pp. 1–4. https://doi.org/10.1109/ICGPR.2016.7572632

Hasegawa, H.S., Wetmiller, R.J., Gendzwill, D.J. 1989. Induced seismicity in mines in Canada—an overview. *Pure and Applied Geophysics*, vol. 129, no. 3, pp. 423–453.

Hashemi, A.S., Katsabanis, P. 2021. Tunnel face preconditioning using destress blasting in deep underground excavations. *Tunnelling and Underground Space Technology*, vol. 117, p. 104126.

Hashemi, A.S., Dadashzadeh, N., Kalenchuk, K. 2023. An Implicit Numerical Modeling Approach for Destress Blasting Design Optimisation for Tunneling and Mine Development in High Stress Conditions. *ISRM Congress*, October 2023 (pp. ISRM-15CONGRESS). ISRM.

He, J., Dou, L., Gong, S., Li, J., Ma, Z. 2017. Rockburst assessment and prediction by dynamic and static stress analysis based on micro-seismic monitoring. *International Journal of Rock Mechanics and Mining Sciences*, vol. 93, pp. 46–53.

Hedley, D.G.F. 1992. Rockburst Handbook for Ontario Hardrock Mines, CANMET Special Report SP92-1E, Energy, Mines and Resources Canada. *Canada Center for Mineral and Energy Technology*, Quebec, p. 305.

Heidarzadeh, S., Saeidi, A., Rouleau, A. 2020. Use of probabilistic numerical modeling to evaluate the effect of geomechanical parameter variability on the probability of open-stope failure: a case Study of the Niobec Mine, Quebec (Canada). *Rock Mechanics and Rock Engineering*, vol. 53, pp. 1411–1431.

Heidarzadeh, S., Saeidi, A., Rouleau, A. 2021. The damage-failure criteria for numerical stability analysis of underground excavations: A review. *Tunnelling and Underground Space Technology*, vol. 107, p. 103633.

Hidayat, W., Sahara, D.P., Widiyantoro, S., Putra, I.P.R.A., Shihab, N.H., Amalia, R., Harisandi, A. 2021. Analysis of Hypocenter Relocation by Using Double Difference Method in a Deep Underground Mining. *IOP Conference Series: Earth and Environmental Science*, October 2021, vol. 873, no. 1, p. 012099. IOP Publishing.

Hill, F.G., Cook, N.G.W., Hoek, E., Pretorius, J.P., Ortlepp, W.D., Salamon, M. 1966. Rock mechanics applied to study of rockbursts. *Journal of the South African Institute of Mining and Metallurgy*, vol. 66, no. 10, p. 435.

Hudyma, M., Potvin, Y. 2004. Seismic hazard in Western Australian mines. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 104, no. 5, pp.265–275.

Hudyma, M., Potvin, Y.H. 2010. An engineering approach to seismic risk management in hardrock mines. *Rock Mechanics and Rock Engineering*, vol. 43, no. 6, pp. 891–906.

Hudyma, M.R., Brummer, R.K. 2007.May. Seismic monitoring in mines-Design, operation, tricks and traps. *1st Canada-US Rock Mechanics Symposium*, May 2007. OnePetro.

Ivanov, B.M., Malinnikova, O.N., Tomilin, P.I. 1980. Methods for determining energy balance during rock bursts. *Nauchn. Soobshch.-Inst. Gorn. Dela im. AA Skochinskogo; (USSR)*, 186.

Jha, P.C., Balasubramaniam, V.R., Sandeep, N., Sivaram, Y.V., Gupta, R.N. 2004. GPR applications in mapping barrier thickness in coal mines: Some case studies. *Proceedings of the Tenth International Conference on Grounds Penetrating Radar*, June 2004. GPR 2004, pp. 605–608. IEEE.

Kabwe, E., Banda, W., Bowa, V.M., Kabwe, E. 2023. Back analysis of the strainburst associated rock fragment ejection in an underground crosscut. *Tunnelling and Underground Space Technology*, vol. 140, p. 105286.

Kaiser, P.K., Cai, M. 2012. Design of rock support system under rockburst condition. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 4, no. 3, pp. 215–227.

Khademian, Z., Ozbay, U. 2019. Modeling violent rock failures in tunnelling and shaft boring based on energy balance calculations. *Tunnelling and Underground Space Technology*, vol. 90, pp. 62–75.

Khademian, Z., Ugur, O. 2018. Computational framework for simulating rockburst in shear and compression. *International Journal of Rock Mechanics and Mining Sciences*, vol. 110, pp. 279–290.

Kidybinski A. 1981. Bursting liability indices of coal. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, vol 18, no. 4. pp. 295–304.

Konicek, P., Waclawik, P. 2018. Stress changes and seismicity monitoring of hard coal longwall mining in high rockburst risk areas. *Tunnelling and Underground Space Technology*, vol. 81, pp. 237–251.

Konicek, P., Soucek, K., Stas, L., Singh, R. 2013. Long-hole destress blasting for rockburst control during deep underground coal mining. *International Journal of Rock Mechanics and Mining Sciences*, vol. 61, pp. 141–153.

Kulich, J., Bleibinhaus, F. 2020. Fault detection with crosshole and reflection geo-radar for underground mine safety. *Geosciences*, vol. 10, no. 11, p. 456.

Labrie, D., Plouffe, M., Haevey, A., Major, C. 1997. *Destress blast testing at Sigma Mine: experimentation and results*. Mining & Mineral Sciences Laboratories.

Lafont, G., Gunzburger, Y., Mitri, H.S., Al Heib, M., Didier, C., Piguet, J.P. 2013. Influence of mining excavation on energy redistribution and rockburst potential. *23rd World Mining Congress*, August 2013 (p. NC).

Li, C.C., Zhao, T., Zhang, Y., Wan, W. 2022. A study on the energy sources and the role of the surrounding rockmass in strainburst. *International Journal of Rock Mechanics and Mining Sciences*, vol. 154, p. 105114.

Li, J., Tang, S., Tang, L., Zhu, C., Liu, Z., Zhao, L., Yang, D., Ma, L. 2023. Study on the characteristics of rockbursts in deep-buried tunnels based on microseismic monitoring. *Environmental Earth Sciences*, vol. 82, no. 14, p. 357.

Li, P., Cai, M., Miao, S., Li, Y., Sun, L., Wang, J., Gorjian, M. 2024. Accurate measurement techniques and prediction approaches for the in-situ rock stress. Scientific Reports, 14(1), p.13226.

Li, P., Liu, Y., Cai, M., Miao, S., Li, Y., Hu, Y., Gorjian, M. 2025. The Overcoring Technique for Precise Measurement of In-Situ Rock Stress at Great Depths: Challenges and Solutions. *Engineering*, vol. 46, pp. 9–15.

Li, X., Gong, F., Tao, M., Dong, L., Du, K., Ma, C., Zhou, Z., Yin, T. 2017. Failure mechanism and coupled static-dynamic loading theory in deep hardrock mining: a review. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 9, no. 4, pp. 767–782.

Lin, H., Oh, J., Masoumi, H., Canbulat, I., Zhang, C., Dou, L. 2018. A review of in-situ stress measurement techniques. *Proceedings of the 2018 Coal Operators' Conference*, February 7, vol. 9, pp. 95–102.

Liu, L., Han, Y., Li, J., Xu, H., Wang, B. 2018. GPR detection of underground void based on low-rank and sparse representation. *2018 17th International Conference on Ground Penetrating Radar (GPR)*, Rapperswil, 2018, pp. 1–4. https://doi.org/10.1109/ICGPR.2018.8441686

Ljunggren, C., Chang, Y., Janson, T., Christiansson, R. 2003. An overview of rock stress measurement methods. *International Journal of Rock Mechanics and Mining Sciences*, vol. 40, nos. 7-8, pp. 975–989.

Lualdi, M., Zanzi, L. 2004. 2D and 3D experiments to explore the potential benefit of GPR investigations in planning the mining activity of a limestone quarry. P*roceedings of the Tenth International Conference on Grounds Penetrating Radar*, June 2004. GPR 2004, pp. 613–616. IEEE.

Luo, S., Gong, F. 2023. Evaluation of energy storage and release potentials of highly stressed rock pillar from rockburst control perspectives. *International Journal of Rock Mechanics and Mining Sciences*, vol. 163, p. 105324.

Ma, X., Westman, E., Counter, D., Malek, F., Slaker, B. 2020. Passive seismic imaging of stress evolution with mining-induced seismicity at hardrock deep mines. *Rock Mechanics and Rock Engineering*, vol. 53, no. 6, pp. 2789–2804.

Ma, X., Westman, E., Slaker, B., Thibodeau, D., Counter, D. 2018. The b-value evolution of mining-induced seismicity and mainshock occurrences at hardrock mines. *International Journal of Rock Mechanics and Mining Sciences*, vol. 104, pp. 64–70.

Malan, D.F., Vogler, U.W., Drescher, K. 1997. Time-dependent behaviour of hardrock in deep level gold mines. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 97, no. 3, pp. 135–147.

Małkowski, P., Niedbalski, Z. 2020. A comprehensive geomechanical method for the assessment of rockburst hazards in underground mining. *International Journal of Mining Science and Technology*, vol. 30, no. 3, pp. 345–355.

Mazaira, A., Konicek, P. 2015. Intense rockburst impacts in deep underground construction and their prevention. *Canadian Geotechnical Journal*, vol. 52, no. 10, pp. 1426–1439.

McMahon, T. 1988. *Rockburst research and the Coeur d'Alene District* (Vol. 9186). US Department of the Interior, Bureau of Mines.

Mendecki, A.J. ed. 1996. Seismic monitoring in mines. Springer Science & Business Media.

Mendecki, A.J., Lynch, R.A., Malovichko, D.A. 2010. Routine micro-seismic monitoring in mines. *Australian Earthquake Engineering Soc., Annual Conference,* Perth, Australia, November 2010, pp. 1–33.

Mertuszka, P., Szumny, M., Fuławka, K., Kondoł, P. 2022. Novel approach for the destress blasting in hardrock underground copper mines. J*ournal of Sustainable Mining*, vol. 21.

Miao, S., Konicek, P., Pan, P.Z., Mitri, H. 2022. Numerical modelling of destress blasting–A state-of-the-art review. *Journal of Sustainable Mining*, vol. 21, no. 4, pp. 278–297.

Minney, D.S., Naismith, W.A. 1993. Quantitative analysis of seismic activity associated with the extraction of a remnant pillar in a moderately deep level gold mine. *Rockbursts and Seismicity in Mines*, vol. 93, pp. 95–100.

Mitri, H.S, Tang, B., Simon, R. 1999. FE modelling of mining-induced energy release and storage rates. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 99, no. 2, pp. 103–110.

Mitri, H.S. 2022. Destress Blasting. ISRM Commission on Deep Mining. Internet. https://www.youtube.com/watch?v=4Pc9W_EqHK0 Accessed 18 March 2022.

Mitri, H.S., Hassani, F.P., Kebbe, R. 1993. A strain energy approach for the prediction of rockburst potential in underground hardrock mines. *Proc., 1st Canadian Symp. Numerical Modelling Applications in Mining and Geomechanics*, May 1993, pp. 228–239). McGill Univ., Montréal.

Modisha, S., Zvarivadza, T. 2015. A review of preconditioning and its influence on mining conditions with particular emphasis on health and safety. P*roceedings of the 24th International Mining Congress and Exhibition of Turkey–IMCET*, vol. 15, pp. 113–122.

Momayez, M., Hassani, F.P., Hara, A., Sadri, A. 1996. Application of GPR in Canadian mines. CIM(Canadian Mining and Metallurgical) *Bulletin*, vol. 89, 1001), pp. 107–110.

Moradipour, M., Hojat, A., Ranjbar, H., Nasab, S.K., Roodposhti, H.R., Daneshpajouh, S. 2015. Application of geophysical methods to determine subsurface acid saturated zones of heap No. 3 at Sarcheshmeh copper mine, Iran. *2015 8th International Workshop on Advanced Ground Penetrating Radar* (IWAGPR), Florence, pp. 1–4. https://doi.org/10.1109/IWAGPR.2015.7292630

Mowrey, G.L., Ganoe, C.W., Monaghan, W.D. 1995. A radar-based highwall rib-thickness monitoring system. *Transactions-Society for Mining Metallurgy and Exploration Incorporated*, vol. 298, pp. 1865–1869.

Murray, W., Lewis, C., Yang, Z., Pollock, J. 1996. Development of high resolution GPR hardware in the frequency range 300 MHz-3.5 GHz. *Proceedings of the 6th International Conference on Ground Penetrating Radar*, September 1996 (GPR'96), pp. 509–510.

Noon, D.A. 1996. Stepped-frequency radar design and signal processing enhances ground penetrating radar performance, *PhD thesis*, Department of Electrical & Computer Engineering, University of Queensland and Cooperative Research Centre for Sensor Signal and Information Processing.

O'Donnell, J.D.P. 1999. The development and application of destressing techniques in the mines of INCO Limited. Citeseer, Sudbury. *MSc Thesis*. Laurentian University, Sudbury, Canada.

Ortlepp, W.D. 1983. 'The mechanics and control of rockbursts', Rock Mechanics in Mining Practice, Budavari (ed.). *Southern African Institute of Mining and Metallurgy*, pp. 257–282.

Papadopoulos, D., Benardos, A. 2021. Enhancing machine learning algorithms to assess rockburst phenomena. *Geotechnical and Geological Engineering*, vol. 39, no. 8, pp. 5787–5809.

Peng, P., He, Z., Wang, L., Jiang, Y. 2020. Microseismic records classification using capsule network with limited training samples in underground mining. *Scientific Reports*, vol. 10, no. 1, p. 13925.

Potvin, Y., Hudyma, M.R. 2001. Seismic monitoring in highly mechanised hardrock mines in Canada and Australia. T*he Fifth International Symposium on Rockburst and Seismicity in Mines, South African Institute of Mining and Metallurgy*, January 2001, pp. 267–280.

Qiu, S., Feng, X., Zhang, C., Xiang, T. 2014. Estimation of rockburst wall-rock velocity invoked by slab flexure sources in deep tunnels. *Canadian Geotechnical Journal*, vol. 51, no. 5, pp. 520–539.

Rahimi, B., Sharifzadeh, M., Feng, X.T. 2020. Ground behaviour analysis, support system design and construction strategies in deep hardrock mining–Justified in Western Australian's mines. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 12, no. 1, pp. 1–20.

Ralston, J.C., Hainsworth, D.W. 1999. Application of ground penetrating radar for coal depth measurement. *1999 IEEE International Conference on Acoustics, Speech, and Signal Processing. Proceedings. ICASSP99*, March 1999 (Cat. No. 99CH36258), vol. 4, pp. 2275–2278. IEEE.

Ralston, J.C., Strange, A.D. 2015. An industrial application of ground penetrating radar for coal mining horizon sensing. *2015 International Symposium on Antennas and Propagation*, November 2015 (ISAP), pp. 1–4. IEEE.

Ralston, J.C., Hainsworth, D.W., Reid, D.C., Anderson, D.L., McPhee, R.J. 2001. Recent advances in remote coal mining machine sensing, guidance, and teleoperation. *Robotica*, vol. 19, no. 5, pp. 513–526.

Rapetsoa, M.K., Manzi, M.S.D., Sihoyiya, M., Malehmir, A., James, I., Socco, L.V., Lepine, J., Colombero, C., Valeshin, O., Durrheim, R.J. 2025. Advanced seismic acquisition techniques in South African mines: Insights from the FUTURE project. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 125, no. 1, pp.25–32.

Reutechmining. 2017. SSP Sub Surface Profiler (Ground Penetration Radar) manual and other documents. Online. https://www.reutechmining.com/ssp/. Accessed: 07/07/2019.

Rojas Perez, C., Wei, W., Gilvesy, A., Borysenko, F.J., Mitri, H.S. 2024. Rockburst assessment and control: a case study of a deep sill pillar recovery. *Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining*, September 2024, pp. 659–672. Australian Centre for Geomechanics.

Roux, A.J.A., Leeman, E.R., Denkhaus, H.G. 1957. Destressing: a means of ameliorating rockburst conditions. Part I: the concept of destressing and the results obtained from its applications. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 57, pp. 101–119.

Saharan, M.R. 2004. Dynamic modelling of rock fracturing by destress blasting. *PhD Thesis*. McGill University, Montreal, Canada.

Sainoki, A., Emad, M.Z., Mitri, H.S. 2017. Study on the efficiency of destress blasting in deep mine drift development. *Canadian Geotechnical Journal*, vol. 54, no. 4, pp. 518–528.

Sainoki, A., Mitri, H.S., Chinnasane, D., Schwartzkopff, A.K. 2019. Quantitative energy-based evaluation of the intensity of mining-induced seismic activity in a fractured rockmass. *Rock Mechanics and Rock Engineering*, vol. 52, pp. 4651–4667.

Sainoki, A., Mitri, H.S., Yao, M., Chinnasane, D. 2016. Discontinuum modelling approach for stress analysis at a seismic source: case study. R*ock Mechanics and Rock Engineering*, vol. 49, pp. 4749–4765.

Salamon, M.D.G. 1970. Stability, instability and design of pillar workings. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, November 1970, vol. 7, no. 6, pp. 613–631. Pergamon.

Salamon, M.D.G. 1974. Rock mechanics of underground excavations, Advances in Rock Mechanics. *Proceedings of 3rd congress of the International Society for Rock Mechanics National Academy of Sciences*, Washington, DC, Denver, pp. 951–1099.

Salamon, M.D.G.1984. Energy considerations in rock mechanics: fundamental results. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 84, no. 8, pp. 233–246.

Salamon, M.G. 1983. Rockburst hazard and the fight for its alleviation in South African gold mines. *Rockbursts: prediction and control. Symposium*, pp. 11–36.

Sampson-Forsythe, A., Andrieux, P., Brummer, R. 2002. Report on the Destress Blast of 24 December 2001 in 42-1-1620 Stope, 080 Access, Fraser Copper Mine. *Report to Fraser Mine*, Falconbridge Ltd.

Sengani, F., Amponsah-Dacosta, F. 2018. The application of the face-perpendicular preconditioning technique for de-stressing seismically active geological structures. *Mining Technology*, vol. 127, no. 4, pp. 241–255.

Sengani, F., Zvarivadza, T. 2017. Review of pre-conditioning practice in mechanised deep to ultra deep level gold mining. *26th International Symposium on Mine Planning and Equipment Selection* (MPES2017). 29–31 August 2017, Luleå, Sweden.

Sengani, F., Zvarivadza, T. 2018a. Borehole periscope observations of rock fracturing ahead of the preconditioned mining faces in a deep level gold mine. *ISRM International Conference on Advances in Rock Mechanics-TuniRock*, March 2018, pp. ISRM-TUNIROCK. ISRM.

Sengani, F., Zvarivadza, T. 2018b. The development and optimization of face-perpendicular preconditioning technique for development ends. *Rock Dynamics and Applications 3*, pp. 349–354. CRC Press.

Sengani, F. 2020a. Characterisation of rock fracturing ahead of the preconditioned mining faces in a hardrock mining. *Arabian Journal of Geosciences*, vol. 13, no. 14, p. 670.

Sengani, F. 2020b. The use of ground Penetrating Radar to distinguish between seismic and non-seismic hazards in hardrock mining. *Tunnelling and Underground Space Technology*, vol. 103, p. 103470. https://doi.org/10.1016/j.tust.2020.103470

Sengani, F., Zvarivadza, T., Adoko, A.C. 2019. Comparison of two adopted face perpendicular preconditioning techniques. *Mining Technology*, vol. 128, no. 1, pp. 21–38.

Shi, X., Cheng, D., Song Z., Wang, C. 2018. A Real-time Method For Landmine Detection Using Vehicle Array GPR. *2018 17th International Conference on Ground Penetrating Radar (GPR)*, Rapperswil, 2018, pp. 1–4. https://doi.org/10.1109/ICGPR.2018.8441584.

Shnorhokian, S., Ahmed, S. 2024a. 3D Modelling of Destress Slots at a Scandinavian Mine. *Rock Mechanics and Rock Engineering*, pp. 1–24.

Shnorhokian, S., Ahmed, S. 2024b. Mechanisms and Measurements of Destressing in Underground Mines: A State-of-the-Art Review. *Mining, Metallurgy and Exploration*, pp. 1–47.

Shnorhokian, S., Mitri, H. 2022. Quantifying the influence of variations in rockmass properties on stope stability. *Journal of Sustainable Mining*, vol. 21, no. 4, p. 331.

Shnorhokian, S., MacNeil, B., Mitri, H.S. 2018. Volumetric analysis of rockmass instability around haulage drifts in underground mines. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 10, no. 1, pp.60–71.

Shnorhokian, S., Mitri, H.S., Moreau-Verlaan, L. 2014 September. Analysis of microseismic cluster locations based on the evolution of mining-induced stresses. *Deep Mining 2014: Proceedings of the Seventh International Conference on Deep and High Stress Mining*, September 2014, pp. 709–722. Australian Centre for Geomechanics.

Shnorhokian, S., Mitri, H.S., Moreau-Verlaan, L. 2015. Stability assessment of stope sequence scenarios in a diminishing ore pillar. *International Journal of Rock Mechanics and Mining Sciences*, vol. 74, pp. 103–118.

Simser, B.P. 2019. Rockburst management in Canadian hardrock mines. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 5, pp. 1036–1043.

Sirait, B., Wattimena, R.K., Widodo, N.P. 2013. Rockburst prediction of a cut and fill mine by using energy balance and induced stress. *Procedia Earth and Planetary Science*, vol. 6, pp. 426–434.

Starfield, A.M., Cundall, P.A. 1988. Towards a methodology for rock mechanics modelling. I*nternational Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, June 1988, vol. 25, no. 3, pp. 99–106. Pergamon.

Sui, Z., Yang, L., Xu, J., Li, C., Chen, T., Ding, C. 2025. Stress interaction and crack penetration mechanism between slit charge blasting holes in high in-situ stress rockmass. *Journal of Geophysics and Engineering*, p. gxaf019.

Swan, G., Li, C.C. 2023. Hardrock burst mechanisms and management strategies. *Geohazard Mechanics*, vol. 1, no. 1, pp. 18–31.

Tajduś, A., Flisiak, J., Cała, M. 1997. Estimation of rockburst hazard basing on 3D stress field analysis. *Ratio*, vol. 1, no. 2, p. 1–6.

Tang, B., Mitri, H. 2001. Numerical modelling of rock preconditioning by destress blasting. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, vol. 5, no. 2, pp. 57–67.

Tang, B. 2000. Rockburst control using destress blasting. *PhD Thesis*. McGill University, Montreal, Canada.

Thebethe, Z. 2018. Assessing preconditioning effectiveness using ground penetrating radar mapping. *MSc Thesis*. University of the Witwatersrand, Johannesburg, South Africa.

Toper, A.Z, Kabongo, K.K, Stewart, R.D., Daehnke, A. 2000. The mechanism, optimisation and effects of preconditioning. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 100, no. 1, pp. 7–15.

Toper, A.Z. 2002. Destressing/preconditioning to control rockbursts in South African deep level gold mines. *International Seminar on Deep and High-Stress Mining. Australian Centre for Geomechanics,* November 2002. Perth.

Toper, A.Z. 2003. The effect of blasting on the rockmass for designing the most effective preconditioning blasts in deep level gold mines. *Doctoral Thesis*. University of the Witwatersrand).

Toper, A.Z., Grodner, M., Stewart, R.D., Lightfoot, N. 1997. Preconditioning: A rockburst control technique. *Rockbursts and Seismicity in Mines*, pp. 267–272.

Toper, A.Z., Janse van Rensburg, A.L., Milev, A.M., Grodner, M.W., Noble, B.R. 2003. Criteria for preconditioning at varying stoping widths in different geotechnical areas. *SIMRAC Project number: GAP, 811.*

Toper, A.Z., Kabongo, K.K., Stewart, R.D., Daehnke, A. 1999. The mechanism, optimisation and effects of preconditioning. *6th International Symposium for Rock Fragmentation by Blasting.*

Van Schoor, M., Nkosi, Z., Magweregwede, F., Kgarume, T. 2022. Deep Level Gold and Platinum Mining: The Application of Geophysics in South Africa. *Springer Nature.*

Vennes, I., Mitri, H. 2017. Geomechanical effects of stress shadow created by large-scale destress blasting. *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 9, no. 6, pp. 1085–1093.

Vennes, I., Mitri, H. 2022. Panel destressing strategies for remnant pillar extraction. *Journal of Sustainable Mining*, 21.

Vennes, I., Mitri, H.S. 2016. Large-scale panel destress blasting parametric study. *3rd International Symposium on Mine Safety Science and Engineering,* November 2016, pp. 65–70.

Vennes, I. 2019. *Improved Ore Recovery in Burst Prone Ground using Destress Blasting* (Doctoral dissertation, McGill University).

Vennes, I., Mitri, H., Chinnasane, D.R., Yao, M. 2020. Large-scale destress blasting for seismicity control in hardrock mines: a case study. *International Journal of Mining Science and Technology*, vol. 30, 2, pp. 141–149.

Verma, R.K., Nguyen, G.D., Karakus, M., Taheri, A. 2024. A size-dependent energy-based strain burst criterion. *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 48, no. 12, pp. 3186–3209.

Wagner, H. 2019. Deep mining: a rock engineering challenge. *Rock Mechanics and Rock Engineering*, vol. 52, pp. 1417–1446.

Walsh, J.B. 1977. Energy changes due to mining. I*nternational Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, January 1977, vol. 14, no. 1, pp. 25–33. Pergamon.

Wang, Y., Li, W., Lee, P.K.K. 1998. Method of fuzzy comprehensive evaluations for rockburst prediction. *Chinese Journal of Rock Mechanics and Engineering*, vol. 17, no. 5, pp. 493–501 (in Chinese). As cited in Cai, M., 2016. Prediction and prevention of rockburst in metal mines–A case study of Sanshandao gold mine. Journal of Rock Mechanics and Geotechnical Engineering, 8(2), pp.204-211.

Wang, C., Si, G., Zhang, C., Cao, A., Canbulat, I. 2021. A statistical method to assess the data integrity and reliability of seismic monitoring systems in underground mines. *Rock Mechanics and Rock Engineering*, vol. 54, no. 11, pp. 5885–5901.

Wang, C., Si, G., Zhang, C., Cao, A., Canbulat, I. 2022. Ground motion characteristics and their cumulative impacts to burst risks in underground coal mines. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 8, no. 1, pp.1–18.

Watson, J., Canbulat, I., Zhang, C., Wei, C. 2025. Energies within rockmass and the associated dynamic rock failures. *Rock Mechanics and Rock Engineering*, pp. 1–24.

Wattimena, R.K., Sirait, B., Widodo, N.P., Matsui, K. 2012. Evaluation of rockburst potential in a cut-and-fill mine using energy balance. *International Journal of the JCRM*, vol. 8, no. 1, pp. 19–23.

Wesseloo, J. 2018. The spatial assessment of the current seismic hazard state for hardrock underground mines. *Rock Mechanics and Rock Engineering*, vol. 51, no. 6, pp. 1839–1862.

Wu, T., Liu, Z., Yan, S. 2024. Detection and Monitoring of Mining-Induced Seismicity Based on Machine Learning and Template Matching: A Case Study from Dongchuan Copper Mine, China. *Sensors*, vol. 24, no. 22, p. 7312.

Xu, H., Apel, D.B., Wang, J., Wei, C., Skrzypkowski, K. 2022. Investigation and stability assessment of three sill pillar recovery schemes in a hard rock mine. *Energies*, vol. 15, no. 10, p. 3797.

Yao, M., Chinnasane, D.R., Sampson-Forsythe, A. 2019. De-Stress Blasting Strategy: Case Studies for Mining in Highly Stressed Sill Pillars at Vale's Ontario Operations. *ARMA US Rock Mechanics/Geomechanics Symposium*, June 2019, pp. ARMA-2019. ARMA.

Yuan, W., Liu, S., Zhao, Q., Deng, L., Lu, Q., Pan, L., Li, Z. 2023. Application of Ground-Penetrating Radar with the Logging Data Constraint in the Detection of Fractured Rockmass in Dazu Rock Carvings, Chongqing, China. *Remote Sensing*, vol. 15, no 18, p. 4452.

Zhang, C., Canbulat, I., Hebblewhite, B., Ward, C.R. 2017. Assessing coal burst phenomena in mining and insights into directions for future research. *International Journal of Coal Geology*, vol. 179, pp. 28–44.

Zhang, M., Hu, X., Huang, H., Chen, G., Gao, S., Liu, C., Tian, L. 2021. Mechanism and prevention and control of mine earthquake in thick and hardrock strata considering the horizontal stress evolution of stope. *Shock and Vibration*, 2021.

Zhang, Q., Zhang, X.P., Liu, Q., Pan, Y., Chi, J., Qiu, J., Yin, X. 2023a. Microseismic Monitoring and Rockburst Characteristics in a Deep-Buried Tunnel Excavated by TBM. *Rock Mechanics and Rock Engineering*, pp. 1–14.

Zhang, X., Yan, P., Lu, W., Pan, X., Liu, X., Zhu, J., Huang, S. 2023b. Energy release and damage characteristics induced by fracture planes in face destress blasting. *International Journal of Impact Engineering*, vol. 173, p. 104485.

Zhao, J.S., Jiang, Q., Lu, J.F., Chen, B.R., Pei, S.F., Wang, Z.L. 2022. Rock fracturing observation based on microseismic monitoring and borehole imaging: In-situ investigation in a large underground cavern under high geostress. *Tunnelling and Underground Space Technology*, vol. 126, p. 104549.

Zhao, Z., Ma, W., Fu, X., Yuan, J. 2019. Energy theory and application of rocks. *Arabian Journal of Geosciences*, 12, pp. 1–26.

Zhou, J., Li, X., Mitri, H.S. 2018. Evaluation method of rockburst: state-of-the-art literature review. *Tunnelling and Underground Space Technology*, vol. 81, pp. 632–659.

Zou, X., Wang, C., Song, H. 2021. Applications of high-resolution borehole image rapid synthesis method for the refined detection of in-suit rockmass structural features during deep buried geotechnical engineering. *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 45, no. 17, pp. 2565–2580.

Zvarivadza, T., Sengani, F. 2018. Practice of face-perpendicular preconditioning for safe remnant extraction. *Rock Dynamics and Applications 3*, pp. 355–359. CRC Press.

Zvarivadza, T. 2023. A conceptual study on the prediction of destress blasting efficiency using geostatistical approaches. *ISRM Congress, October 2023* (pp. ISRM-15CONGRESS). ISRM.

Zvarivadza, T., Onifade, M., Dayo-Olupona, O., Said, K.O., Githiria, J.M., Genc, B., Celik, T. 2024. On the impact of Industrial Internet of Things (IIoT)-mining sector perspectives. *International Journal of Mining, Reclamation and Environment*, vol. 38, no. 10, pp. 771–809. ◆