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Preventive pillar reinforcement methodology incorporating instrumentation and extraction strategy at the Chuquicamata underground mine

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Abstract

The mining method used at the Chuquicamata underground mine is post-undercut block caving, in which, after the base of the block is undercut, the natural caving and fragmentation of the rock mass occurs. The behaviour of rock pillars at Chuquicamata underground evolves through 2 main stages. The first stage corresponds to the response to stresses induced by the advancing cave front (abutment stress), representing a pre-connection period during which production level pillars begin to deform and cracking develops. The second stage occurs after connection to the surface, when the pillars experience increased deformation due to deconfinement, directly affecting the installed ground support.

This study focuses on the preventive definition of reinforcement measures for production pillars, with the objective of anticipating further increases in deformation and ensuring the stability of the productive areas. The analysis is based on seismic activity, where variations in apparent volume and energy index are evaluated to identify increasing deformation and a reduction in stress levels (loss of confinement). These responses are validated using pillar extensometer measurements, drift scanning and assessments of production excavations and local geotechnical conditions.

Based on the evaluation of these responses, different reinforcement alternatives are jointly defined with the mine operational teams. These alternatives are required to be coordinated with the production plans of each productive area.

This approach enables the development of a preventive pillar reinforcement plan, together with an extraction strategy aimed at controlling deformation increments across different zones, thereby ensuring the stability and continuity of the mine's productive areas.

Keywords: *Chuquicamata underground mine, block caving, geotechnical risk, rock pillars, geomechanical instabilities*

1 Introduction

The Chuquicamata underground mine, operating since 2019 beneath the former open pit (Figure 1), employs large-scale block caving across 4 active macroblocks with an extraction footprint of 152,000 m² and a production rate of 80 ktpd. Cave propagation and the caving-induced stress redistribution generate significant abutment loading on production-level pillars, while structural collapses within the cave contribute to the formation of oversized blocks that exacerbate local stress concentrations.

Pillar instabilities are primarily associated with advanced deformation during abutment stress cycles and subsequent deconfinement as the cave connects to the surface, reducing the pillars' residual load-bearing capacity and occasionally interrupting caving continuity. Ground response is not violent, and is monitored

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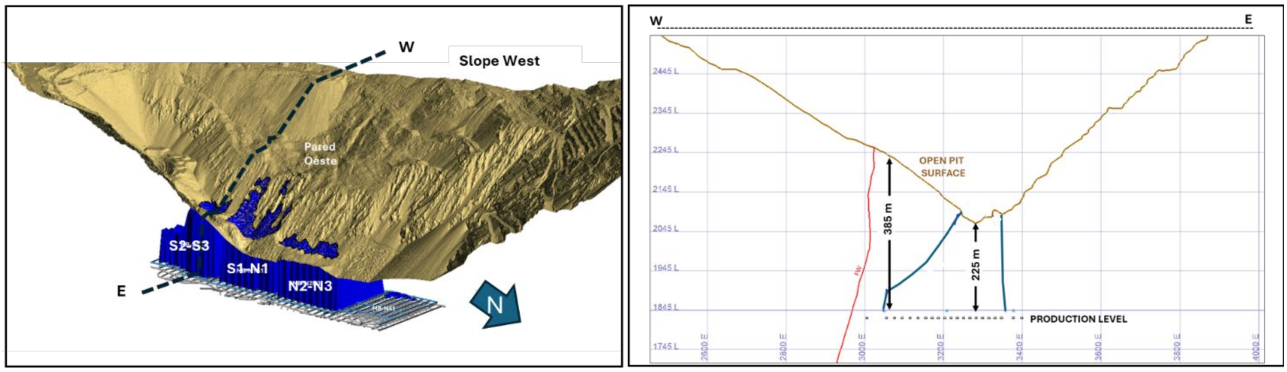
through extensometry and laser-based convergence measurements, providing early detection of deformation trends and supporting management of geomechanical stability.



(a) (b)

Figure 1 (a) Operational macroblocks at Chuquicamata underground mine and Chuquicamata open pit. (b) Vertical distance between the production level and the pit bottom.

Ground control and rock support become important levers in the mine construction schedule, production performance and excavation health (Moss & Kaiser 2022). In this line, large convergence events In caving operations present significant challenges and threats to safety and productivity (Palacio et al. 2024).

This paper presents the working methodology applied in the macroblocks of the Chuquicamata underground mine to address pillar deformations, covering the process from the planning stage through to the operational stage. This methodology enabled an improvement in the capacity of the installed ground support through the implementation of preventive reinforcement at early stages. The success of pillar stability depends not only on the correct field implementation of the preventive reinforcement design, but also on a sequence of integrated stages, including blast QA/QC and adherence to the extraction plan, among others.

2 Background of Chuquicamata underground

2.1 Geology and geotechnical units

This chapter shows the basic geological and geotechnical information of the deposit which provides an overview of the different alteration and mineralisation processes that gave rise to the Chuquicamata deposit.

The macroblocks are predominantly located within the Quartz-Sericite unit, which is further subdivided into three major units according to its geological genesis and the relative abundance of quartz and sericite. These units were defined according to different degrees of alteration and mineralisation (Vásquez et al. 2023). The units are known as PEK (Potassic), PES (Sericitic) and RQS (Quartz Sericitic). Depending on the quartz-sericite content, the RQS unit is further divided into QIS (Q = S), QMES (Q <S) and QMS (Q> S).

The rock mass strength properties were provided by the mine in terms of standard rock mass parameters (density, σci, GSI and m_i) for each unit and the Americana Fault Zone.

The geotechnical-structural model shows good agreement with the geological models, highlighting the Americana Fault, as a structural feature controlling the boundaries between alteration and mineralisation units. The structure is characterized by a north–south trending fault zone comprising multiple fault strands and reaching an overall width of approximately 40 m

According to Constanzo & Harisson (2019), drilling campaigns, in-person mapping of underground worksite cells, and collection of structural data have made it possible to identify and characterise the following basic geotechnical units (BGUs), based on geological-geotechnical characteristics, degree of alteration and the presence of major structural features:

- Potassic East Porphyry (PEK): this unit is characterised by preserving certain textural and mechanical properties of the original rock, behaving as a competent unit with good to very good quality.
- Sericitic East Porphyry (PES): this unit has been observed as a gradual contact zone between the PEK and RQS units. It is characterised by partial destruction of the original texture and a strong structural control over its distribution.
- Quartz Sericitic Rock (RQS): this alteration appears intrusively, obliterating the entire original texture of the rock that forms the East Porphyry. Within the RQS unit, 3 subunits can be distinguished based on their quartz-sericite content:
  - Quartz Equal Sericite (QES) – quartz content between 30% and 70%
  - Quartz Greater Sericite (QGS) – quartz content greater than 70%
  - Quartz Lesser Sericite (QLS) – quartz content less than 30%.

The properties from tests at both intact rock and rock mass scale are shown in Table 1 for MB N2-N4.

Table 1 Properties of intact rock and rock mass – MB N2-N4

BGU	ρ (g/cm^3)	UCS_{50} (MPa)	E_i (GPa)	υ	σ_{ci} (MPa)	m_i	GSI
PEK	2.616	94.96	47.62	0.23	84.59	17.78	60
PES	2.663	73.67	47.65	0.26	71.31	23.02	59
QIS	2.728	70.52	43.89	0.24	68.6	12.75	57
QMES	2.7	20.3	9.39	0.26	22.82	19.49	44

2.2 Structural condition

The principal structures identified and interpreted within MB N03 to MB S03 can be classified (Figure 2) based on their occurrence, magnitude and spatial extent – taking varying observation scales into account – into the following hierarchical categories:

- First-order structures: these occur at the deposit or district scale. They exhibit the highest relative displacement between blocks, resulting in a well-developed fault rock fabric.
- Second-order structures: present either individually or as a system beyond the central zone limits of the deposit. These structures also demonstrate significant relative block displacement, leading to considerable development of fault rocks.
- Third-order structures: located within the referenced macroblocks (MB N03 to MB S03), these structures are characterised by minor thicknesses of associated fault rock or, in some cases, an absence thereof.
- Fourth-order structures: structures localised within the macroblocks, either restricted to certain areas or distributed across one or multiple macroblocks.

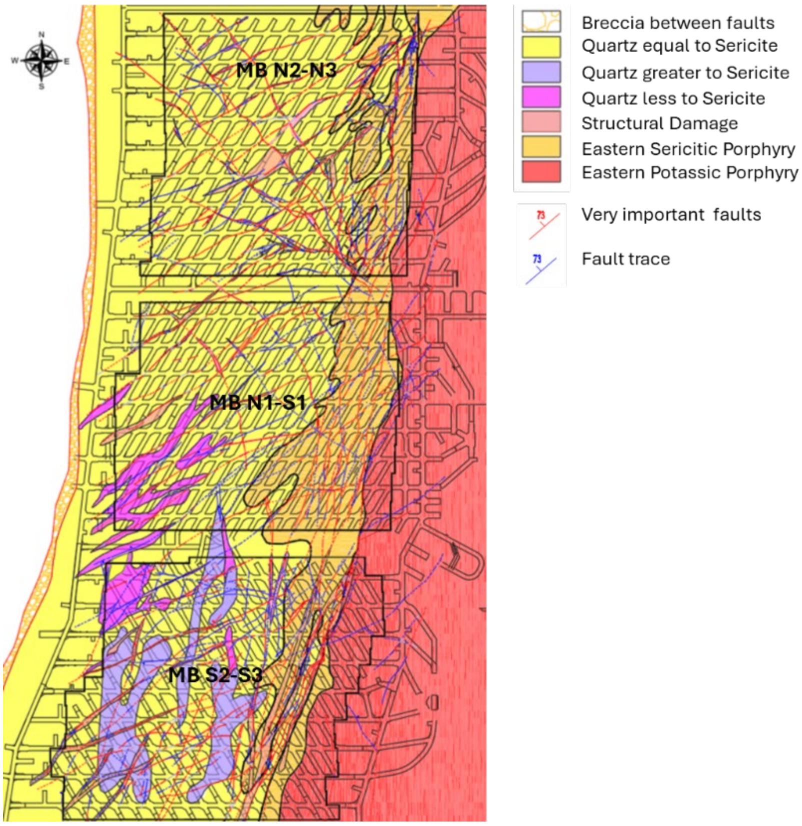


Figure 2 Geotechnical-structural model at production level – elevation 1823

2.3 Stress state

The stress state of the Chuquicamata underground mine is estimated using a mine-scale three-dimensional numerical model, which has been calibrated with a stress measurement database of data collected between 2016 and 2021 (Barindelli & Valdes 2024) using the Hollow Inclusion and Acoustic Emission techniques. Table 2 presents the estimated average stress state for the MB N01–S01 sector of the Chuquicamata underground mine under pre-mining conditions after open pit excavation. It is important to note that the stress conditions in other macroblocks show variations from the indicated values, mainly due to factors related to the distribution and competence of the BGUs, as well as the in situ column height beneath the topography of the Chuquicamata open pit mine.

Table 2 Pre-mining stress state

Stress	Magnitude (MPa)	Azimuth (°)	Plunge (°)
σ_1	22.1	13.9	10.5
σ_2	18.6	283.3	3.4
σ_3	16.3	175.7	79.0

3 Methodology

Since the commencement of mining operations, pillar deformation events have been reported, resulting in impacts on operational continuity. These deformations arise from a combination of contributing factors, as shown in Table 3.

Table 3 Factors contributing to deformation in pillars in Chuquicamata underground mine

Category	Contributing factors
Geology	Poor ground in QMES Major faults across the pillar Damage zone around the major faults
Design	Small pillars Irregular geometry
Construction	Overbreak in excavation, reduced pillar area
Cave sequence	Long abutment residency times
Cave geometry	Irregular extraction front Excessive lead-lags between undercutting front and extraction front
Blasting	Overbreak in drawbell in one stage
Support	Inadequate ground support installation Loss of capacity of support

The methodology was designed to address all identified contributing factors, which were individually resolved in close collaboration with the geotechnical, planning, design and operations teams. Three main stages were identified within the process:

- Stage 1: the first stage focused on understanding the response of the pillars under imposed loading conditions, considering the geotechnical-structural setting and the installed ground support.
- Stage 2: this stage involved improvements in mine preparation, mine design, ground support implementation, blasting practices, and the caving sequence.
- Stage 3: finally, an appropriate monitoring system was established to enable the definition and implementation of early warning thresholds during mining operations.

Experience gained indicates that effective prevention of high pillar deformation events requires the early involvement of the operational geomechanics team during the engineering process. This involvement is particularly critical during the pre-mining stage, where geomechanical input supports the identification of vulnerable zones and the definition of ground support and instrumentation designs. During the mining stage, the role of operational geomechanics is focused on geomechanical monitoring and the timely implementation of reinforcement support measures. Figure 3 presents a conceptual framework illustrating the stages of the methodology applied for the management of pillar deformation at the Chuquicamata underground mine.

Figure 3 Geomechanical methodology for pillar deformation management in Chuquicamata underground mine

3.1 Pillar reinforcement

The production level pillars, specifically in the drift section and in both low- and high-speed curves, are strengthened with reinforced concrete panel walls of variable height ranging from 3.05 to 3.55 m, reaching up to the tunnel's spring line. This provides increased confinement to the pillar during the early stages of induced stress. The confinement wall has a thickness of 20 cm and is constructed with G-50 concrete. It includes double-strand central-tied cables (ø15.64 mm, A416270 steel, 6 m of anchorage at the hole bottom), helical bolts (ø22 mm, A440-28 steel, 3.5 m long in rock) and Acma C-665 mesh, arranged as shown in Figure 4 in plan and profile views.

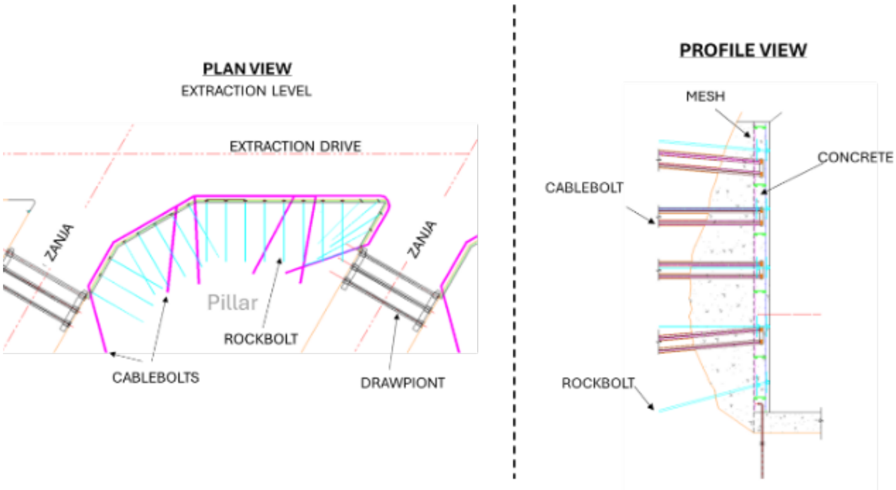


Figure 4 Plan and profile views of general reinforcement – confinement wall for production pillars

To ensure correct onsite implementation, the operational geomechanics team has developed quality control checklists for each activity carried out by the contractor. These checklists must be signed and approved by the shift supervisors and ultimately received by the field geomechanics personnel.

3.2 Monitoring

Deformation observed in the production level pillars is systematically assessed through in situ geomechanical field evaluations. Additionally, deformation is monitored using extensometers, complemented by topographic laser scanning to accurately capture geometric changes.

3.2.1 In situ deformation mapping

Field observations are conducted daily by the operational geomechanics team (Torres 2024) and are officially reported on drawings once a month. The deformation mapping methodology considers the confinement wall reinforcement installed on the pillars as the baseline. Deformation ratings are assigned based on the observed condition of the structural elements contributing to the wall's resistance (concrete, anchor bolts, mesh and tie cables), shown in Figure 5.

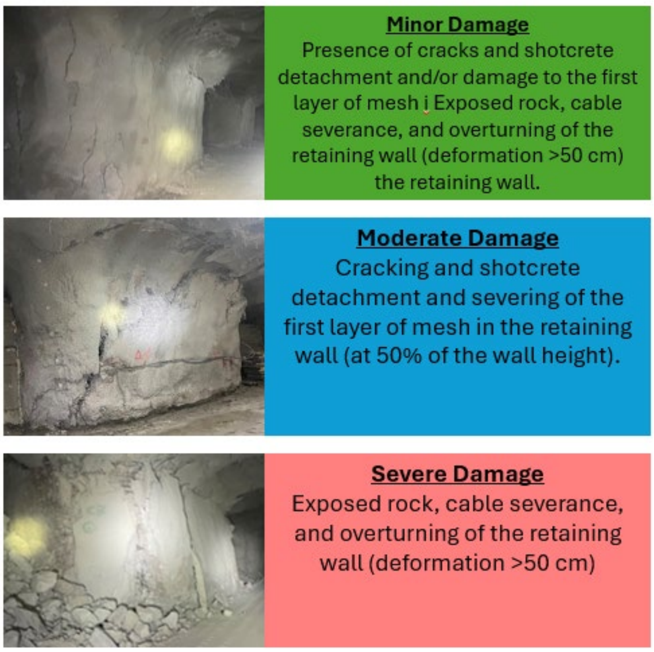


Figure 5 Deformation evaluation criteria for production level pillars

The pillar deformation process can be divided into 2 main stages: pre-surface breakthrough and post-surface breakthrough, with the following field observations identified for each stage (Lopez et al. 2024):

- Pre-surface connection stage: this stage corresponds to the initial incorporation of new mining areas, during which pillars are affected by induced stresses resulting from the advancement of the cave front. Observations during this phase include cracking and delamination of shotcrete in corners, and the formation of fractures in reinforced concrete walls. The onset of pillar deformation is recorded with the drawbell blast, prior to the cave front's arrival. As the cave front advances and the abutment stress phase develops, deformation to the pillars increases, particularly in those intersected by major fault systems. During this stage, pillar deformation is typically classified as minor to moderate.
- Post-surface connection stage: this phase begins once the cave front has reached the surface, initiating surface breakthrough. Field observations include increased cracking, structural disintegration of the pillar, and in some cases, overturning of the confinement wall – especially in pillars that exhibited significant pre-existing deformation. In this stage, deformation severity ranges from moderate to severe (Figures 6 and 7).

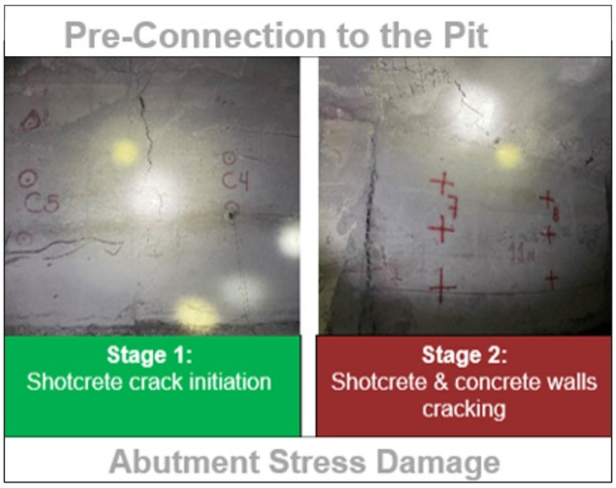


Figure 6 General reinforcement: damage condition of confinement wall for production level pillars, Stages 1–2

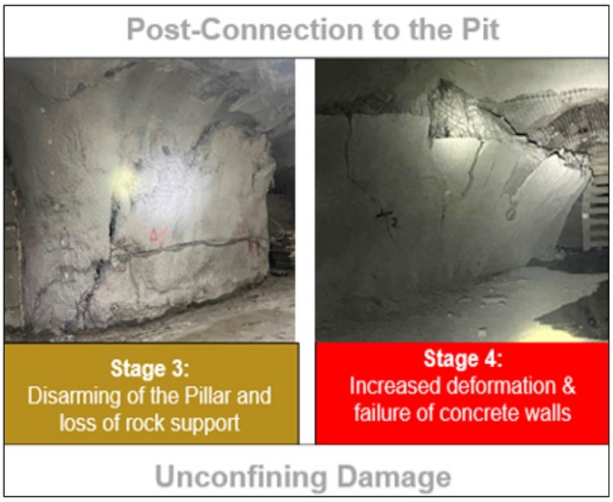


Figure 7 General reinforcement: damage conditions of confinement wall for production level pillars, Stages 3–4

3.2.2 Seismic monitoring

At the Chuquicamata underground mine, seismic monitoring is the primary source of information for anticipating changes in rock mass response associated with cave propagation and its eventual connection to the surface. In block caving, the fracturing of the rock mass and the movement of blocks toward the void release energy in the form of seismic events. For this reason, the underground seismic network plays a central role in tracking cave development and assessing its influence on areas of geomechanical interest.

At the time of this study, the mine-wide monitoring system consisted of 50 installed geophones, most of them triaxial, with natural frequencies of 4.5 and 14 Hz. Figure 8 presents the average seismic sensitivity at the production level (elevation 1823), together with the distribution of the installed sensors, indicated by triangles, and the corresponding event location uncertainty. In the productive area, the average sensitivity at this elevation is approximately −1.5, which is within the range commonly associated with routine mine-scale seismic monitoring. Event locations are therefore generally better constrained within the denser central part of the array and become progressively less constrained toward its margins. Source parameters such as energy and potency are used mainly for comparative analyses, since their uncertainty is influenced by array geometry, signal quality and processing assumptions (Mendecki et al. 1999).

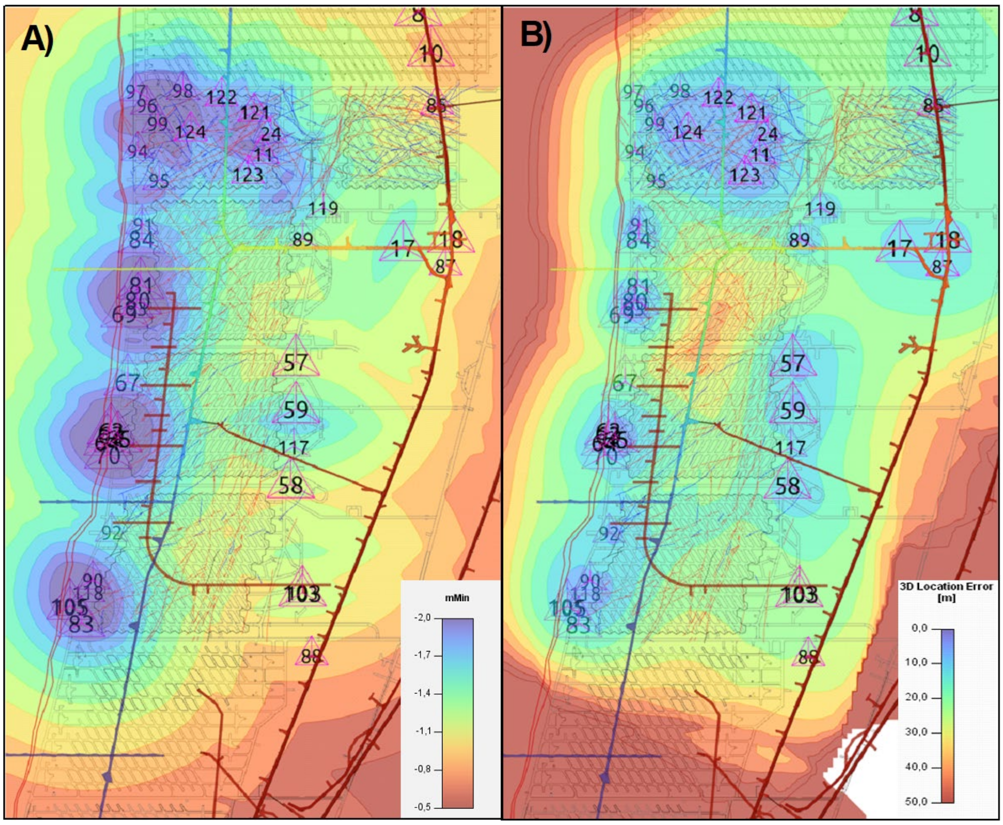


Figure 8 Seismic system coverage and location quality at production level (elevation 1823). (a) Average seismic sensitivity, with installed seismic sensors (geophones) shown as triangles; (b) Spatial distribution of event location uncertainty within the monitored volume

The main parameters used for this purpose are event frequency, energy index and accumulated apparent volume. Figure 9 presents an example of the seismic monitoring system and the main indicators commonly used to assess rock mass response. Figure 9a shows the seismicity recorded by the underground seismic network between 1 January 2026 and 21 March 2026, while Figures 9b–9d present accumulated apparent volume, event frequency and energy index, respectively. Considered together, these variables help identify spatial and temporal changes in rock mass condition, recognise zones of elevated activity, and follow the transition from relatively higher-stress areas to lower-confinement conditions. Within this framework, the energy index is interpreted as a relative indicator of stress state, whereas accumulated apparent volume is used as a proxy for inelastic seismic deformation (Mendecki 2012).

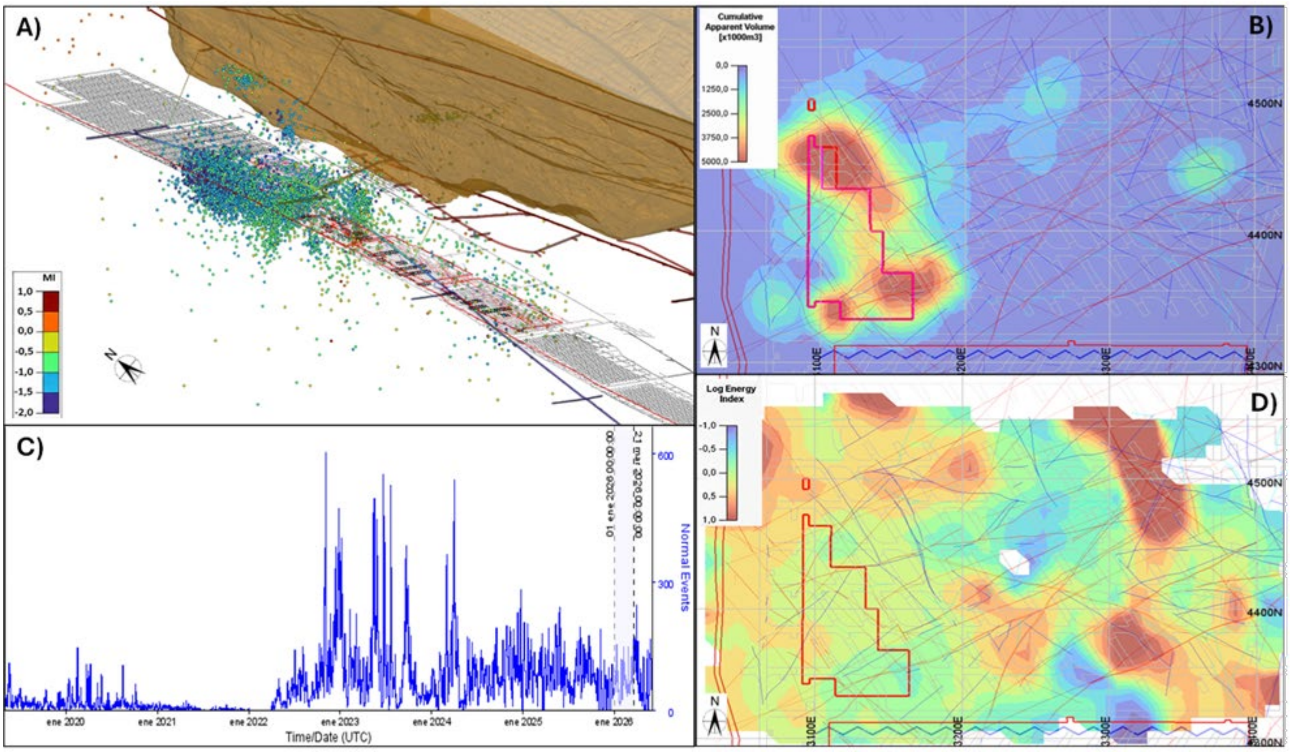


Figure 9 Example of seismic monitoring system and main seismic indicators used to assess rock mass response. (a) Seismicity recorded by the underground seismic network between 1 January 2026 and 21 March 2026; (b) Accumulated apparent volume for MB N41 from 7 to 21 March 2026; (c) Event frequency; (d) Energy index for MB N41 from 7 to 21 March 2026

In interpretative terms, the evolution of energy index makes it possible to recognise different stages of rock mass response as mining progresses. Higher energy index values are generally associated with more confined sectors and higher relative stress conditions, commonly observed as the cave front approaches a given zone. As the front advances through that zone, the energy index tends to decrease, reflecting a transition toward relaxation and lower confinement. In this stage, accumulated apparent volume becomes increasingly relevant, as its growth reflects a greater expression of seismic deformation within the rock mass. Under this approach, the combined interpretation of these parameters makes it possible to distinguish sectors with higher relative stress from those evolving toward lower confinement and higher deformation potential. Figure 10 presents an example of this evolution by comparing spatial distributions of log energy index from 2 periods of cave front advance with a temporal detail of energy index and accumulated apparent volume during the transition period.

This interpretation highlights the potential of seismic monitoring to identify areas where the rock mass may be evolving towards higher deformation potential and where further geomechanical assessment is warranted. In this study, the seismic response is considered a preliminary indicator of changes induced by cave front advance. Energy index and accumulated apparent volume are therefore interpreted as relative indicators of the evolving rock mass response, rather than as direct measures of absolute stress. The example shown in Figure 10 should consequently be understood as an illustration of how seismic data can guide the selection of areas for detailed review, not as a standalone basis for reinforcement or support maintenance decisions. These areas are subsequently assessed using deformation records, complementary geotechnical instrumentation and field observations, allowing support decisions to be based on an integrated interpretation of seismicity, deformation and field conditions.

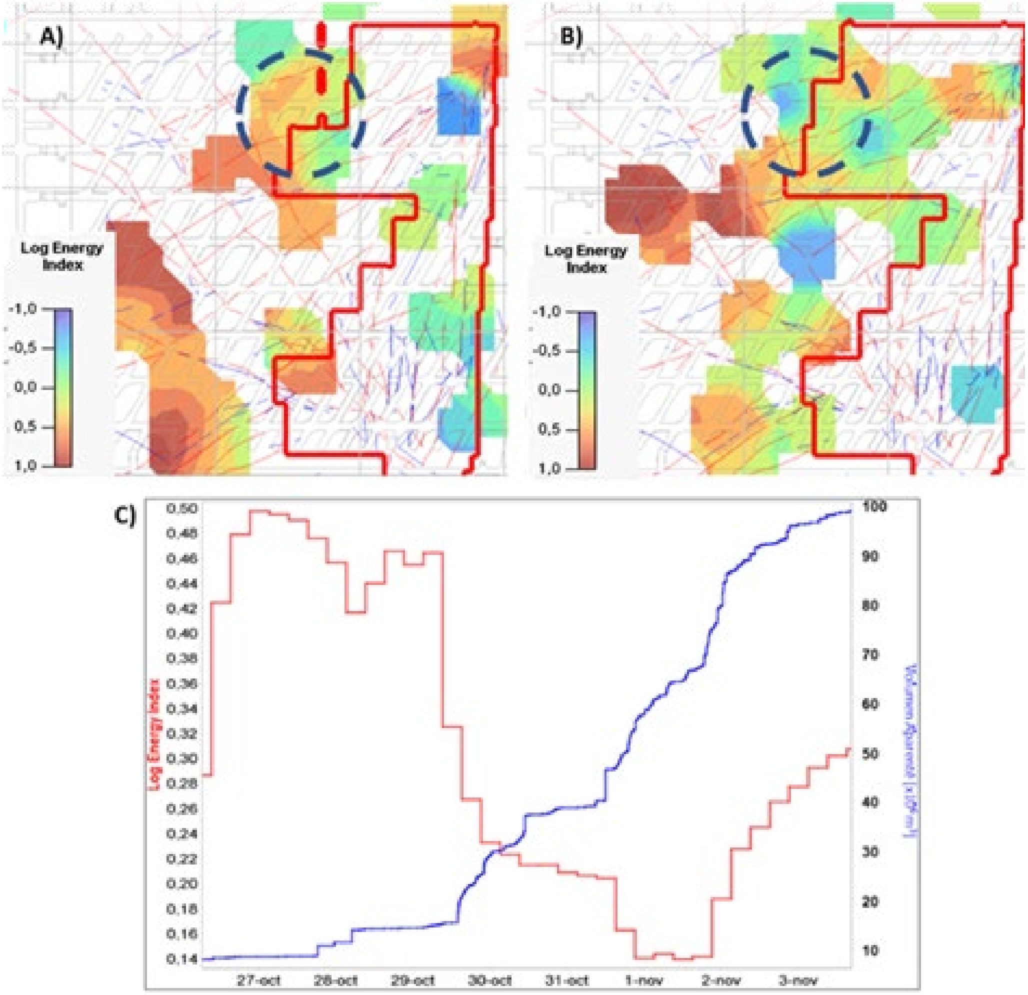


Figure 10 Illustrative example of spatial and temporal seismic response during cave front advance. (a) Spatial distribution of log energy index for 14 to 28 October 2022; (b) Spatial distribution of log energy index for 1 to 15 November 2022; (c) Temporal detail of log energy index and accumulated apparent volume from 26 October to 4 November 2022. The red line indicates the cave front position for each period. Dashed circles indicate areas selected for visual comparison between the 2 periods

3.2.3 Pillar deformation monitoring using extensometers

To measure pillar deformation, 12 m-long rod extensometers are used, with anchors installed at 3 m intervals. These are distributed in the corners and crown sections of the excavation, as illustrated in Figure 11.

Field implementation is governed by an installation protocol, which outlines the required procedures for proper grout application, instrument activation and subsequent monitoring. Data are transmitted online via digital dataloggers installed on the instrument heads, which are connected to a gateway that relays information in real time to the server. The placement of extensometers in the field was determined based on the deformation potential of the pillars, taking into account the underground mine's expansion and the zones of weakness within the rock mass – specifically, pillars located at lithological contacts and intersected by major fault systems. Figure 12 shows the location of extensometers within MB S02-S03.

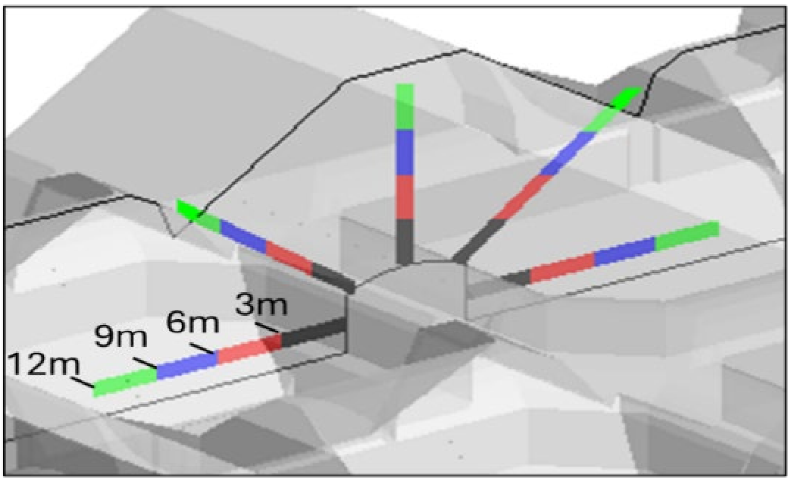


Figure 11 Positioning of extensometers within the pillar

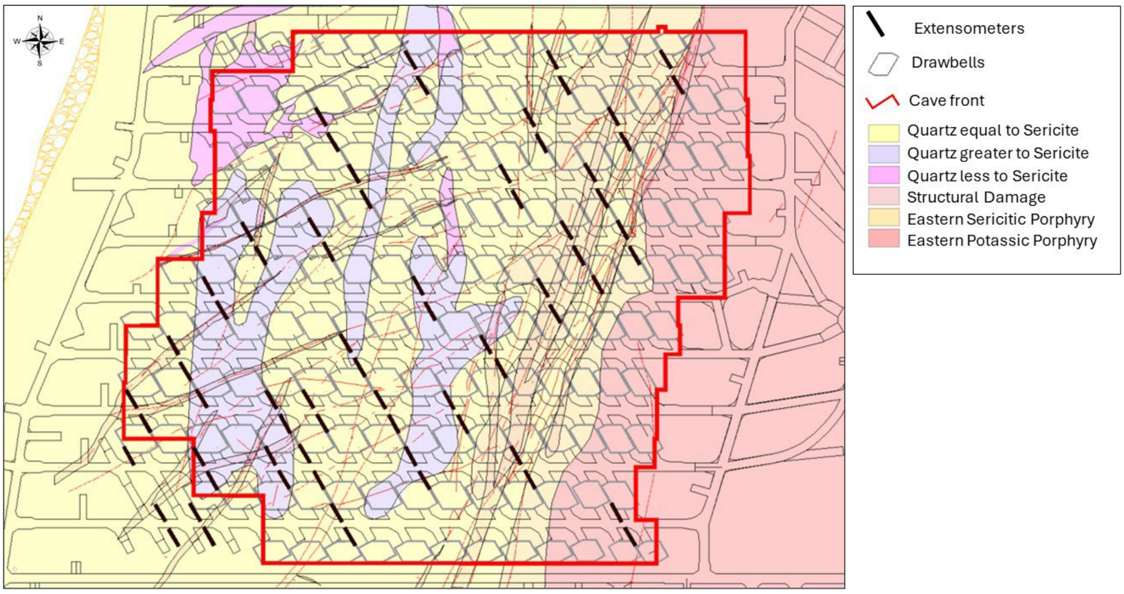


Figure 12 Distribution of extensometers in Macroblock S03

A study conducted in MB S02-S03 of the Chuquicamata underground mine identified the main operational activities inherent to the caving method that influence pillar deformation as measured by extensometers. This made it possible to correlate changes in the deformation curve of the extensometers with specific mining activities (Zepeda et al. 2024).

The primary activities that generate changes in the deformation curve (Figure 13) are as follows:

1. Onset of mechanical loading on the pillar, associated with induced stress conditions resulting from the advance of the caving front.
2. Drawbell blasting operations.
3. Radial blasting at the undercut level.
4. Surface breakthrough process.

An example of extensometer behaviour is presented in Figure 13, highlighting the stages that produce the greatest impact on pillar deformation.

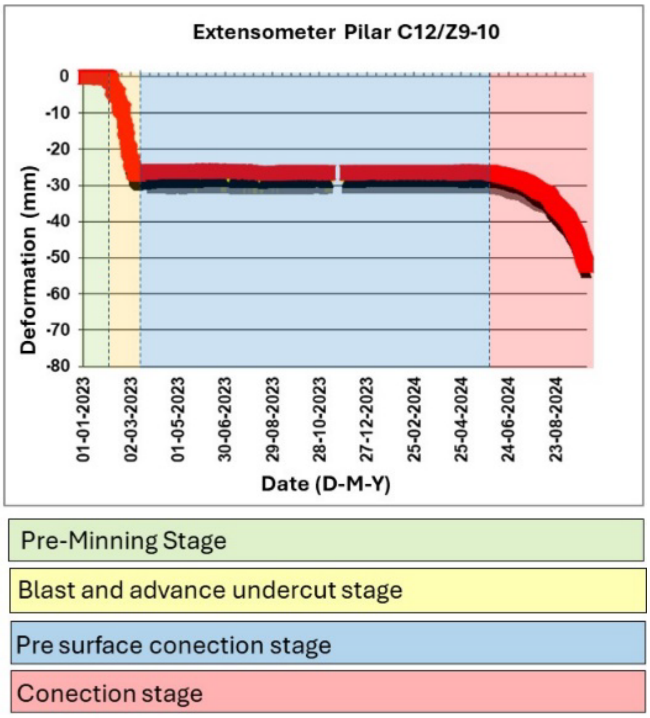


Figure 13 Deformation processes affecting pillar strength, represented by extensometer behaviour

3.2.4 Monitoring with laser scanner

In addition to field observations and extensometer monitoring, tunnel deformation is analysed using laser scanning. For this purpose, I-Site scanners are used to establish the baseline shortly after construction and prior to the start of production. This baseline is then compared against data collected using the handheld ZEB-Horizon scanner (Figure 14), which allows for rapid and dynamic data acquisition in the field, proving especially useful in areas exhibiting deformation.

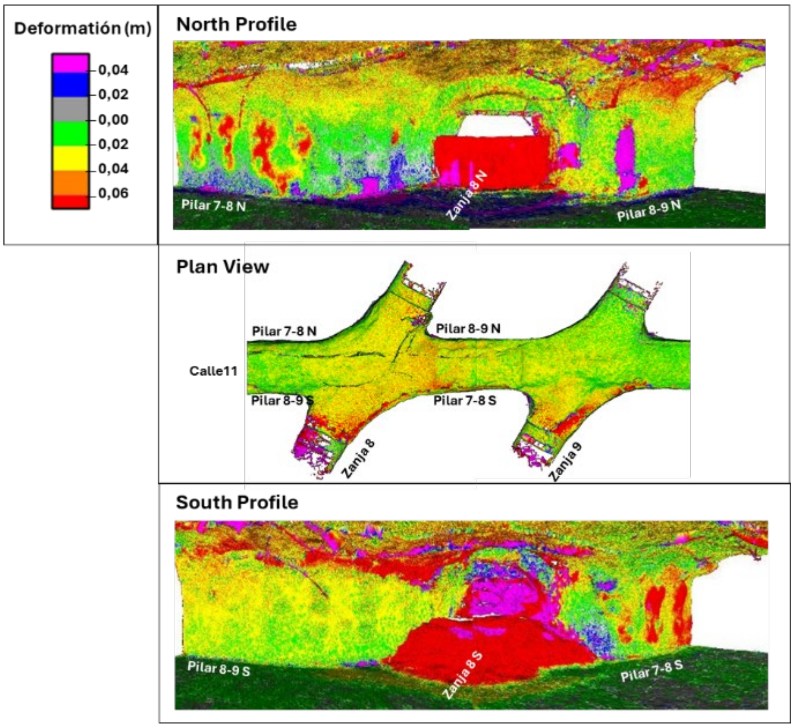


Figure 14 Plan and profile views of deformation analysis using laser scanning in pillars located along Drift 11 between drawpoints Z8–Z9, representing areas with light to moderate deformation

3.3 Pillar reinforcement strategy

The pillar reinforcement strategy involves implementing a fortification design (Barindelli & Valdes 2024) that provides increased load-bearing capacity and deformation resistance to the pillar. The fortification design includes the installation of 27 double-strand cables, distributed over 9 rows, each with a length of 11 m anchored into the rock. The cables are sheathed in their central section and anchored in the core of the pillar – an internal portion that remains unaffected by induced stresses and has not experienced degradation, as shown in Figure 15.

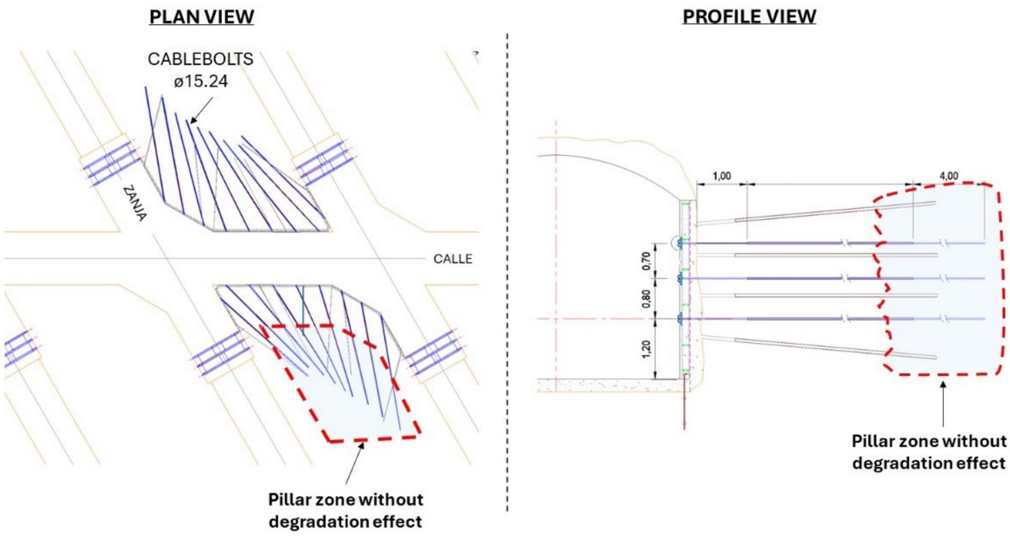


Figure 15 Plan and profile views of fortification design applied for preventive pillar reinforcement

The pillar reinforcement design is applied based on the following considerations:

- Pillars subjected to induced stress due to the advance of the caving front: this applies to all pillars that show deformations greater than 4 cm, as measured by laser scanning and extensometers.
- Pillars located near collapse zones: reinforcement is applied to 'encapsulate' the deformation area and prevent the propagation of deformation to surrounding pillars.
- Pillars located in areas with deformation potential, such as zones of faulting, lithological contacts, poor geotechnical quality, or with a high percentage of overbreak.

The priority for reinforcement is determined based on deformation rate and total accumulated deformation, in accordance with the defined TARP (trigger action response plan) for collapses.

Most of the pillar collapses at the production level have occurred in pillars located behind the caving front, which, due to their high-deformation levels (>6 cm), are unable to withstand the changes in stress conditions caused by the growth of the caving zone and the passing of the surface connection front. For this reason, all pillars are reinforced after the caving front passes and before the surface connection front reaches them.

Additionally, increased deformation has been observed in pillars located around collapse zones (Vásquez et al. 2024). This has led to the implementation of a reinforcement strategy aimed at 'encapsulating' the collapse area and preventing deformation propagation to adjacent pillars.

The pillar reinforcement program has been in effect since August 2023, with a gradual increase in volume and compliance. To date, a total of 161 pillars have been reinforced: 82 in MB S02-S03, as shown in Figure 16.

The preventive reinforcement plan considers multiple variables such as:

- the fortification design
- scheduling of activities by drift
- availability of power supply and ventilation services
- interaction between extraction and reinforcement activities
- drift closure time
- and availability of equipment and supplies.

In addition to the preventive pillar reinforcement process, significant efforts have been made in developing an extraction strategy and field control measures that enable a concave growth of the connection front and a cavity geometry free of irregularities.

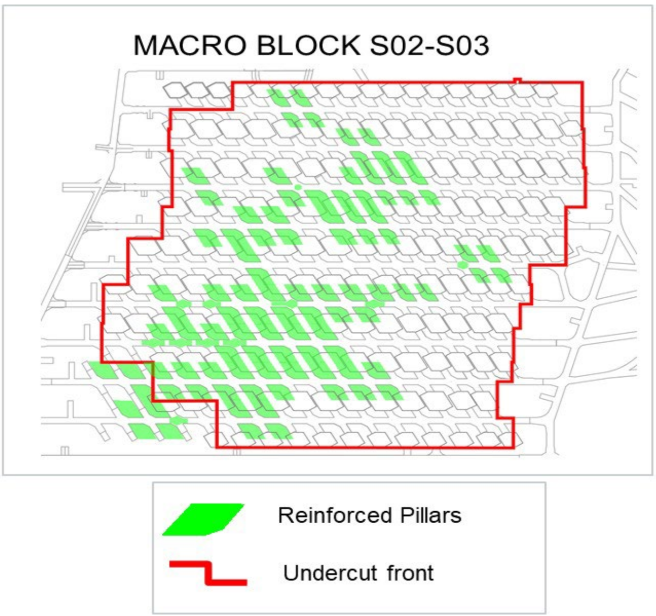


Figure 16 Reinforced pillars in MB S02-S03

While the preventive pillar reinforcement strategy has proven effective in enhancing pillar confinement and operational continuity, several limitations were identified during its implementation. First, the availability of specialised equipment and skilled labour constrained the execution pace of reinforcement activities in some drifts. Additionally, ventilation and power supply requirements occasionally delayed the construction of confinement walls in active extraction zones, requiring rescheduling of reinforcement phases. Monitoring data also presented challenges due to occasional signal loss or data transmission interruptions in high-deformation areas, impacting the continuity of real-time deformation tracking.

4 Conclusion

Most of the deformations in the galleries originating from the Chuquicamata underground mine are related to the deconfinement condition induced by the surface connection, which causes block opening and subsequent degradation of the rock mass.

The implementation of preventive pillar reinforcement has improved the pillars' response to the unloading process caused by the surface connection. Since April 2024, this has resulted in a reduction of area loss due to instabilities behind the caving front and a slowdown in deformation propagation around pillars.

It is crucial to implement a continuous deformation monitoring system for pillars and establish evaluation criteria based on field observations, enabling timely and quality preventive pillar reinforcement.
The preventive pillar reinforcement process must be applied in conjunction with a strategy that considers variables for the proper management of extraction and caving propagation, and it must be monitored through seismicity and deformation control.

Future work will aim to incorporate microseismic monitoring data to better correlate deformation patterns with local seismic responses and to anticipate potential failure mechanisms in highly stressed pillars. Additionally, numerical modelling of pillar behaviour, calibrated with in situ monitoring data, could further optimise reinforcement design parameters and prioritise intervention timing. Expanding the preventive reinforcement strategy to include more comprehensive risk assessment criteria – considering lithological variability, structural features and stress path evolution – may also improve the identification of vulnerable pillars before critical deformation occurs. Finally, lessons learned from the Chuquicamata case could be applied to similar large-scale block caving operations worldwide, contributing to safer and more resilient underground mining practices.

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