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Criteria for mining area postponed due relevant seismicity and its impact on caving propagation, El Teniente mine

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ABSTRACT

In 2016, it was decided to postpone mining area ahead front of Bloque-2 of Esmeralda Mine, due to the occurrence of relevant seismic events in the development area (exposure of personnel). This deferred area, named "Postponed Polygon (P.P.)", encompassed a total area of 8,800 m^2 and would be re-evaluated in the future to demonstrate a favorable geomechanical environment for the resumption of development and mining operations in the P.P. The primary proposal to induce a change in the geomechanical conditions involves continuing to advance towards the south and east of the postponed area, with the aim of modifying stress conditions through the development of a cavity connected to the upper levels. The conditions of the polygon were corroborated through the assessment of several parameters such as: geomechanical damage survey (evaluation of the support system in galleries), seismic parameters related to the maximum recorded event and the evolution of the energy index, mining activity in terms of drawbell commissioning and extraction heights of Bloque-2. The integrated analysis of these data confirmed the favorable geomechanical conditions of the deferred sector, allowing the resumption of development and construction activities, progressing with the blasting of drawbells and the extraction of the postponed area to generate a uniform global cavity in Block-2.

1 INTRODUCTION

The mining of primary ore at Codelco El Teniente mine began in 1982 (Figure 1). This type of mineral pertains to a harder type of rock, with lower average grades, resulting in coarser fragmentation compared to the secondary ore, which was also being extracted at that time. Later, Load-Haul-Dump (LHD) equipment was introduced to extract and transport the mineral to ore pass. This was the main difference from the conventional block caving method. Other differences included an increase in block height, larger open areas for extraction, and the systematic drawbells mining of caved areas (dynamic caving front). All of this occurred in a complex geological environment with high stresses, resulting in stability problems. These were new to the operation and included gallery overbrakes, structural collapses, and rock bursts.

In addition to the implementation of the Panel Caving Variant, a series of internal studies, controls, and tests, mainly of a geomechanical nature, have been carried out to address the numerous questions raised regarding the stability of the galleries constructed in primary rock. These studies have been primarily related to: Conceptualization of the Caving Propagation Stages, Implementation of Hydraulic Fracturing, Support Systems, and Mining Variants (Pardo et al., 2016). Currently, the mining variant implemented in the El Teniente mining complex corresponds to Post-undercutting with Hydraulic Fracturing.

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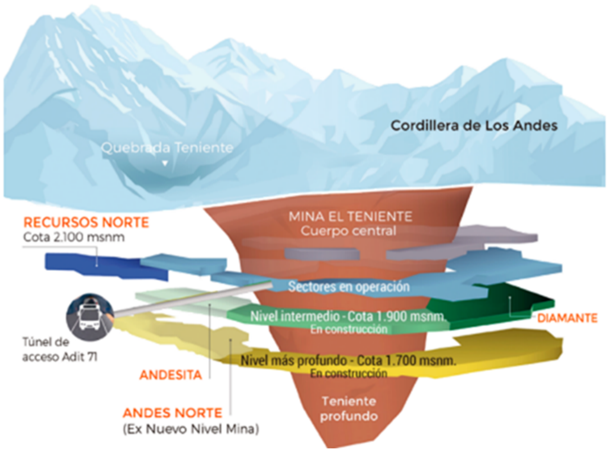


Figure 1 **Two patterns with different explosives.**

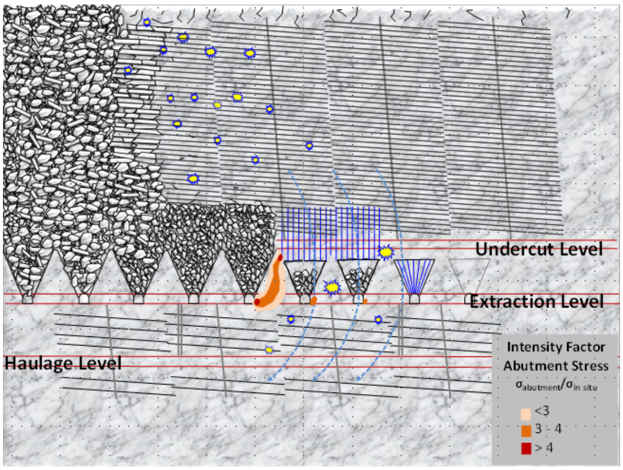


Figure 2 **Post-undercut Panel Caving with Hydraulic Fracturing.**

2 CENTRAL MINE

2.1 Located

El Teniente mining complex consists of several productive sectors located at different depths around the Braden Pipe, with the Upper Pacific being the sector closest to the surface at elevation 2,265 m, and the Recursos Norte the deepest located at elevation 2,120. Together, they generate an approximate production of 140 ktpd. The distribution of these sectors is shown in Figure 3.

Central Mine is located on the southwest side of the deposit and is composed of several productive sectors: Bloque-1, Bloque-2, Panel 1 y Panel 2, with an approximate production of 45 ktpd, with Bloque-1 and Bloque-2 contributing 75% of the sector's total production.

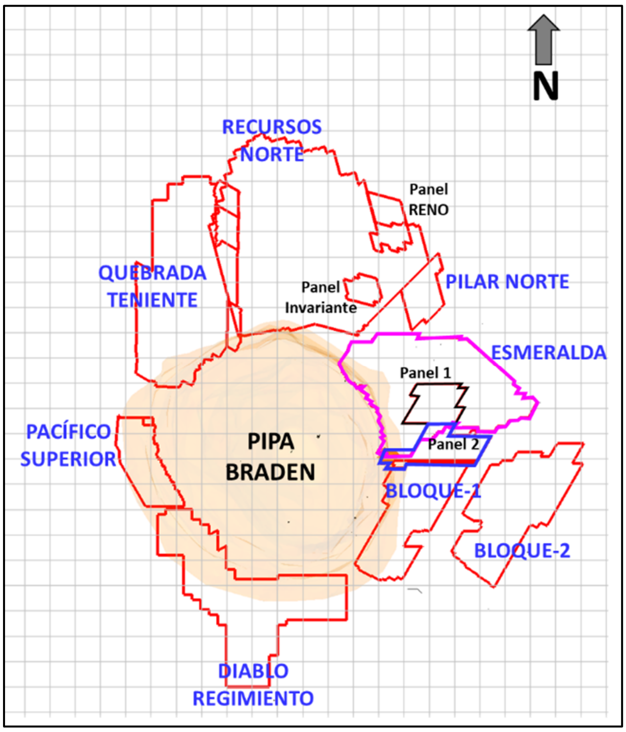


Figure 3 **View plant El Teniente mining complex.**

2.2 Bloque-2

Bloque-2 is in the South-Eastern area of the El Teniente mining complex, south of Esmeralda Mine and east of Bloque-1. It is mining ploited through Post-undercutting Panel Caving with Hydraulic Fracturing. The elevations of the caving and production levels are 2,211 and 2,193 meters respectively. The geological characteristics of the sector are consistent with primary rock, being the main lithologies El Teniente Mafic Complex (CMET) and Tonalite, as well as some intrusive rocks such as Anhydrite Breccia, Coarse Porphyry Dioritic Breccia, Tourmaline Breccia, and Biotite Breccias. Regarding the characteristic stress state pre-mining, the values associated with the principal stresses are: $\sigma_1 = 45$ MPa; $\sigma_2 = 30$ MPa; $\sigma_3 = 20$ MPa. The direction of the major principal stress has an azimuth of 340° and a dip of 20°. See Figure 4.

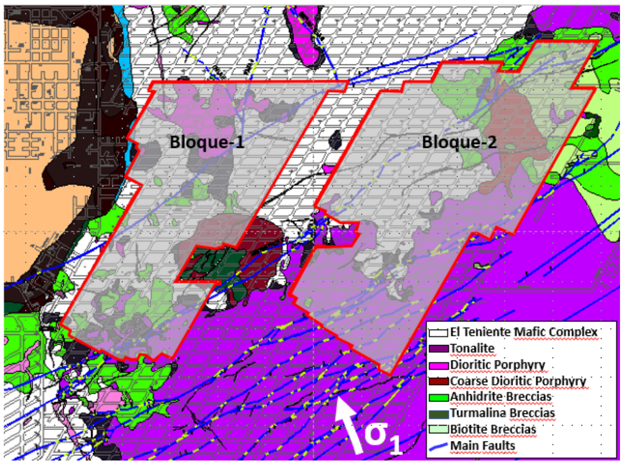


Figure 4 Bloque 1, Bloque-2, Geology, Principal Faults and Principal Major Stress.

2.3 *Beginning Bloque-2*

On July 18, 2012, the mining of Bloque-2 of Esmeralda Mine began using Post-undercutting with Hydraulic Fracturing, conducting the first blast drawbell located at between drifts C-57 and C-59. Subsequently, the advance of Bloque-2 proceeded continuously until the connection of the caving with the caved upper level (Teniente 4 Sur Mine) during October 2013 (Orellana et al., 2014). Following this process, Bloque-2 maintained sector growth towards the south until relevant seismic activity was recorded ahead of the caving front, in an area where drifts development and civil works construction were underway. Due to this condition, the advancement towards the south continued with a front width of 150 meters.

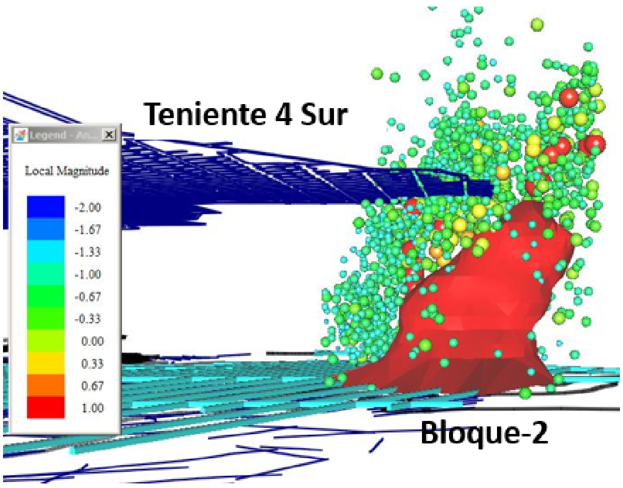


Figure 5 Bloque 2 connecting process with caved upper level Teniente 4 Sur Mine.

3 POSTPONED MINING AREA

3.1 *Relevant Seismicity*

During the months of December 2015 and July 2016, 5 events with a magnitude greater than 1.0 were recorded in front of Block-2 of Esmeralda Mine, mainly located in the vicinity of the production level, as observed in Figure 6 and 7. These events were recorded in an area undergoing tunnel development, thus exposing workers to this seismic condition. The characteristics of the relevant events are those outlined in Table 1.

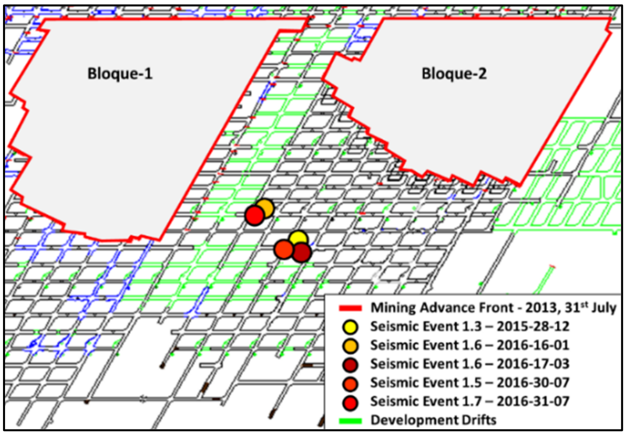


Figure 6 Relevant seismicity ahead caving front Bloque 2.

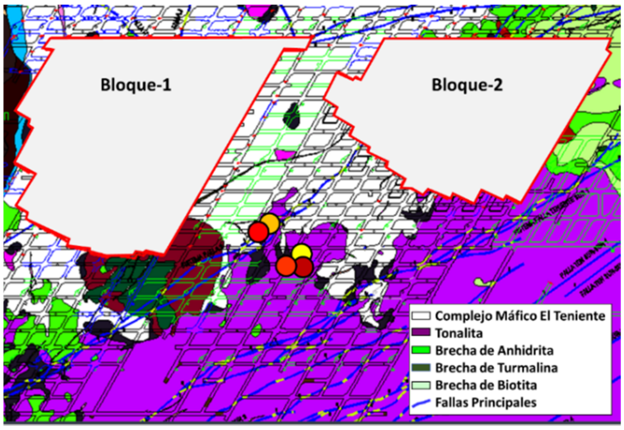


Figure 7 Relevant seismicity ahead caving front Bloque 2, geology and principal faults.

Table 1 Characteristics of previous relevant events

Date	Magnitud	Energy (J)	Heigh (m)
28-12-2015	1.3	3,2 x 10^5	2202
17-01-2016	1.6	3,5 x 10^5	2184
17-03-2016	1.6	8,5 x 10^5	2188
30-07-2016	1.5	1,1 x 10^6	2180
31-07-2016	1.7	2,5 x 10^6	2190

3.2 Postponed Polygon

Due to the increasing magnitude and energy of seismic activity and the location at an elevation around the production level (2.193 m), the decision was made to postpone the affected area until favorable conditions and geomechanical environment were present for mining developments. Under the seismic conditions mentioned above, the maximum recorded seismic event corresponds to a magnitude of 1.9ML. Consequently, the postponed area covers 11,040 m^2, specifically between C-49 to C-43 and from Z-44 to Z-48 (Figure 8). It is important to note that when projecting the postponed polygon at the UCL, the area was already developed (Figure 9).

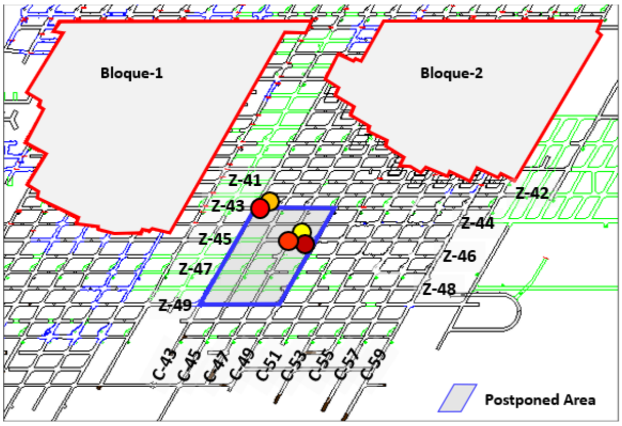


Figure 8 Postponed polygon in production level.

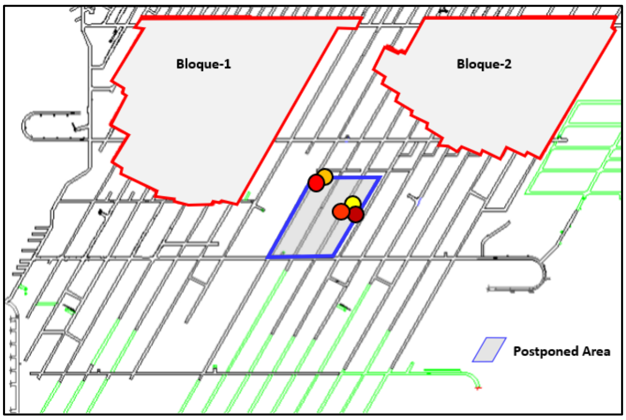


Figure 9 Postponed polygon projected at UCL.

From the above, the progress towards the south would be through the sector where developments were already completed. It should be noted that the postponed zone was a restricted area for any person.

3.3 Mining Bloque-2

The mining advancement towards the south proceeded continuously in accordance with the production plans. The following figure shows the progression of mining activity up to June 2022, the date when the geomechanical evaluation of the postponed polygon was conducted.

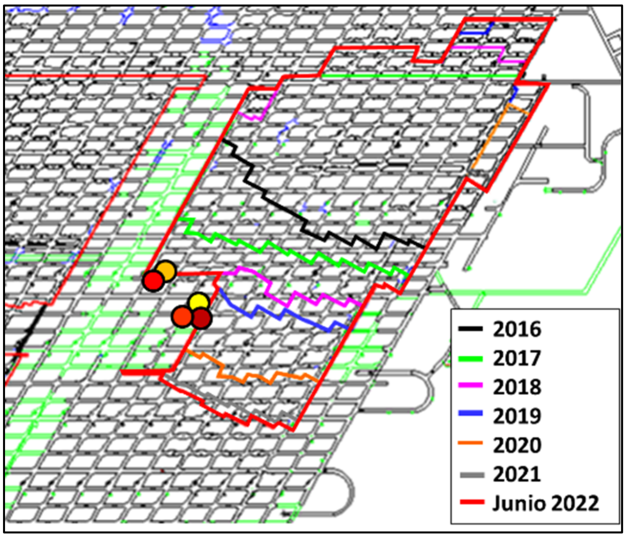


Figure 10 Progression of Bloque-2.

4 GEOMECHANICAL ASSESSMENT POSTPONED POLYGON

4.1 Mining Assessment

A relevant factor for the assessment postponed polygon relates to the mining activities carried out in the adjacent to P.P. The progression of the caving front during the period from 2016 to 2022 as observed in Figure 11. This advancement was conducted in accordance with the production plans, and by June 2022, the extraction heights associated with Block-2 are as specified in Figure 12 and 13, considering that the maximum height of primary rock column is 150 meters.

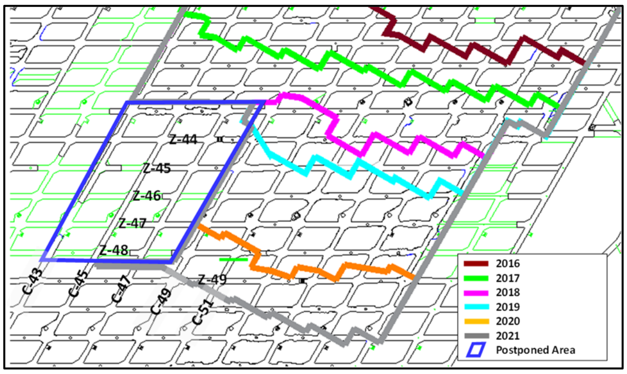


Figure 11 Progression of the caving front adjacent to the postponed polygon.

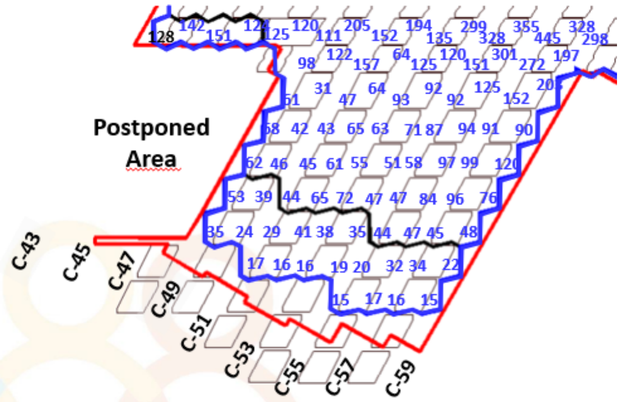


Figure 12 Extraction heigh Bloque-2, June 2022.

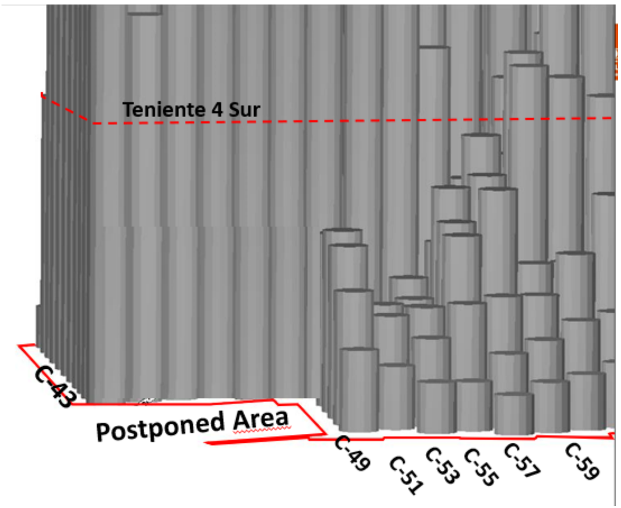


Figure 13 Extraction heigh Bloque-2, June 2022.

4.2 Seismic Parameters Assessment 2018-2021

4.2.1 Maximum Recorded Magnitude

The follow assessment is about to the seismicity record of the postponed zone during the period 2018-2021, with the aim of considering the seismic response of the postponed polygon. In this review of seismicity recorded during the mentioned period, it is possible to observe a decrease in the maximum event recorded within a defined volume on the ground by the postponed polygon and within 70 meters above and below the UCL. According to Figures 14 to 17, the maximum recorded event decreased from 1.7ML in 2018 to 0.9ML during 2021 within the considered volume.

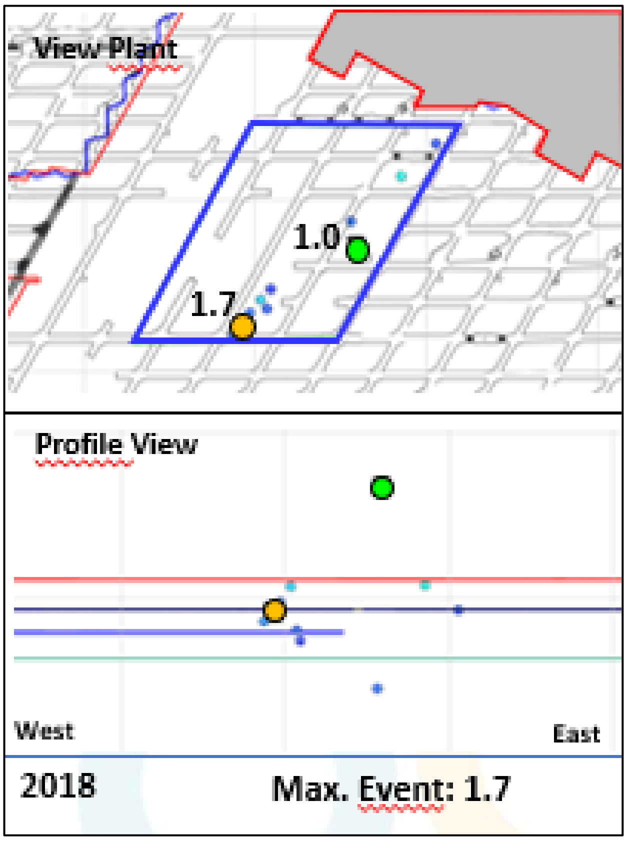


Figure 14 Seismicity recorded in 2018 Mw≥1.0

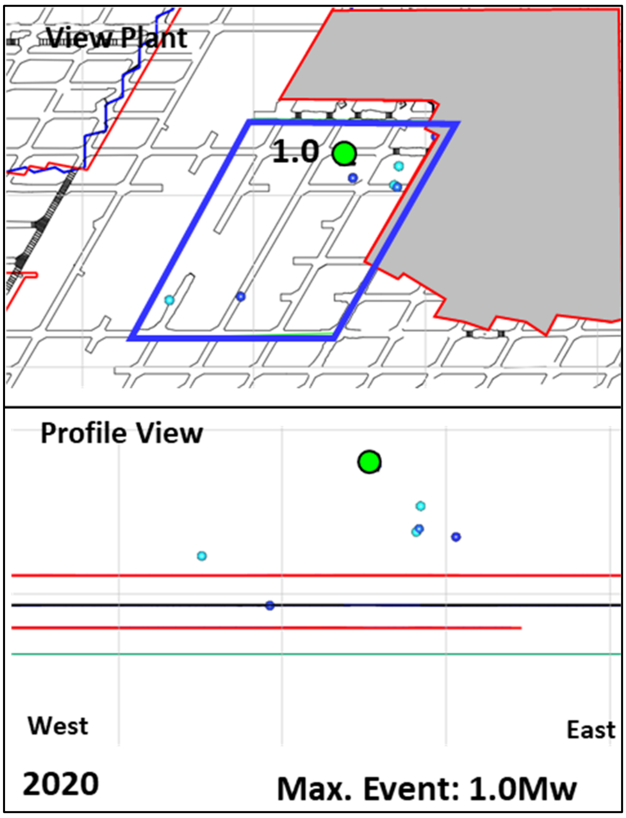


Figure 16 Seismicity recorded in 2020 Mw≥1.0.

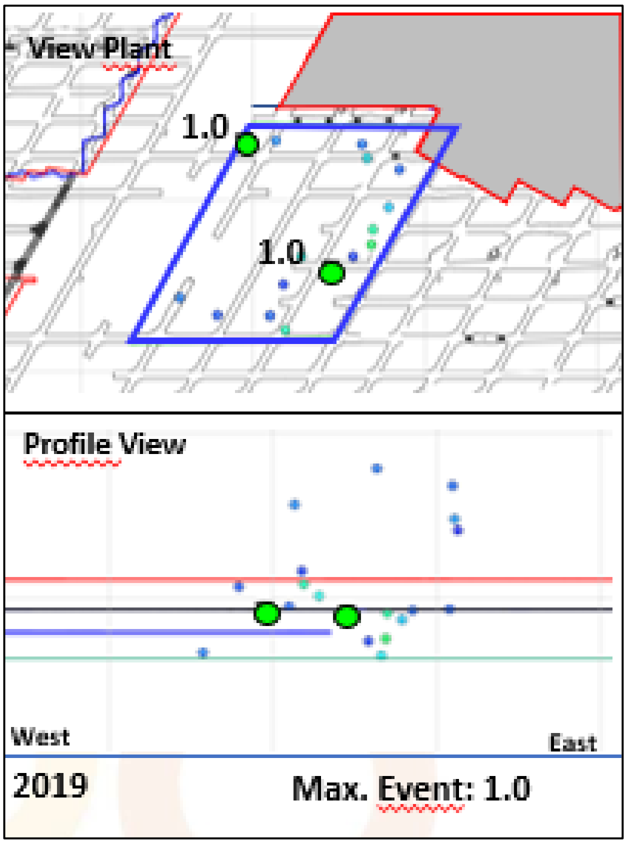


Figure 15 Seismicity recorded in 2019 Mw≥1.0.

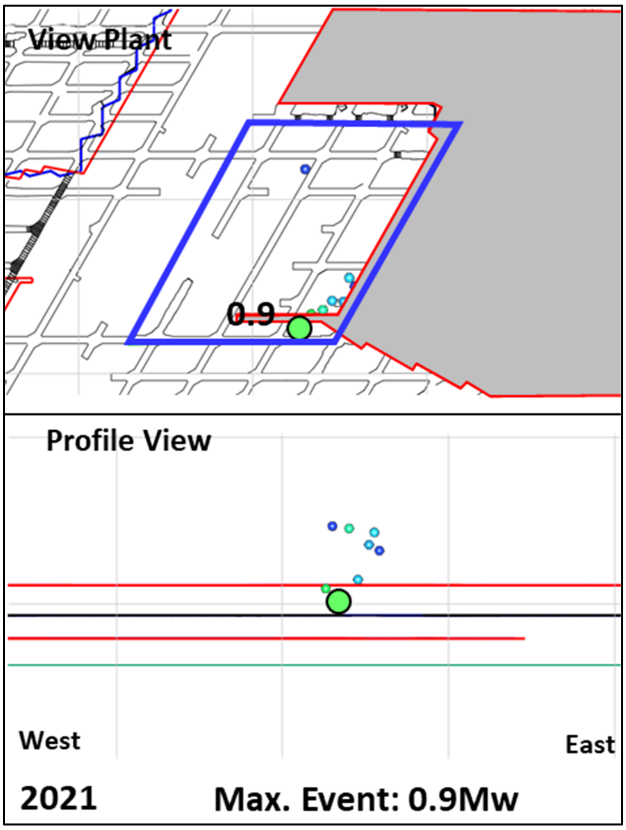


Figure 17 Seismicity recorded in 2019 Mw≥1.0.

Table 2 Characteristics of events

Date	Magnitude	Energy (J)	Heigh (m)
10-03-2018	1.7	3.2×10^6	2267
25-09-2018	1.0	6.6×10^4	2191
18-05-2019	1.0	1.3×10^5	2190
01-07-2019	1.0	7.6×10^4	2192
29-03-2020	1.0	7.8×10^3	2280
30-08-2021	0.9	$4{,}9 \times 10^3$	2188

4.2.2 Energy Index

Another seismic parameter analyzed is related to the Energy Index, which was plotted for the same volume and period as the maximum recorded events. According to Figures 18 to 21, this parameter has shown a decrease in its values during the period 2018-2021.

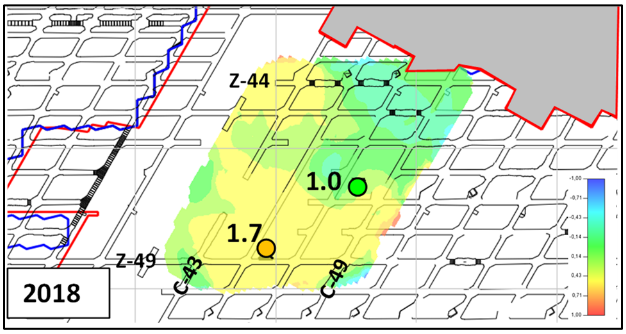


Figure 18 Energy index 2018 – Medium-High Level.

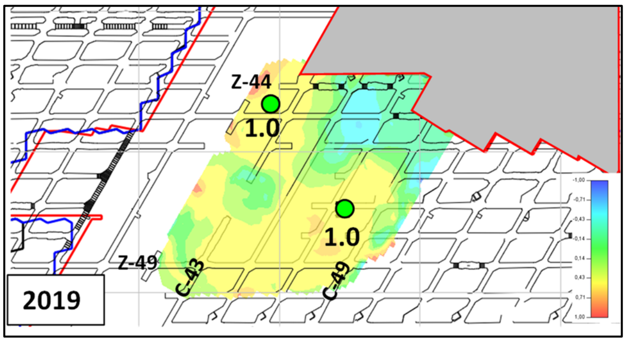


Figure 19 Energy index 2019 – Medium-High Level.

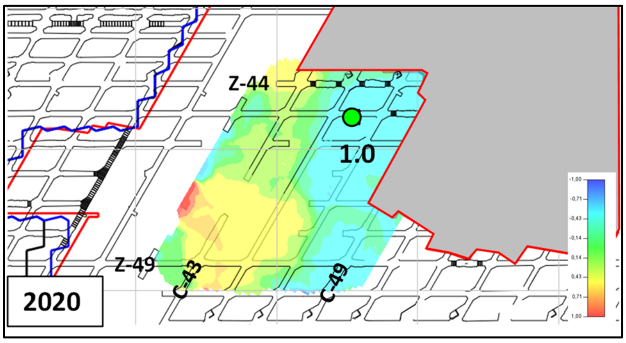


Figure 20 Energy index 2020 – Medium-Low Level.

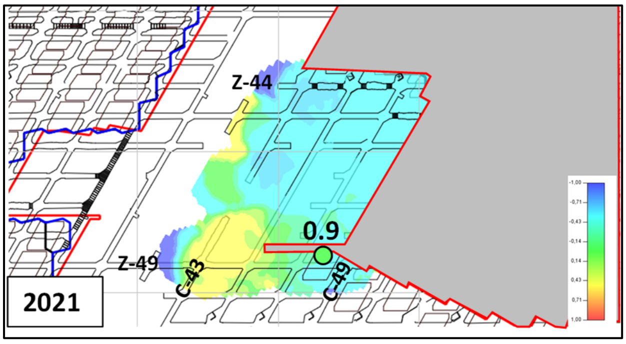


Figure 21 Energy index 2021 – Low Level.

4.3 Geomechanical Damage Survey

The next topic to assess is the support system of the drifts in the zone of interest. The geomechanical assessment standard for the condition of galleries in the El Teniente mining complex due to the abutment stress effect is related to intensity of damage observable in the tunnels. For the geomechanical assessment of the support system state, three levels are established: Slight Damage, Moderate Damage, and Severe Damage. The definition of each of these items is as follows:

- **Slight Damage**: Slight cracking or flaking of shotcrete.
- **Moderate Damage**: Presence of loaded mesh and/or bulging of the support system.
- **Severe Damage**: Loss of support system, fortification not working (exposed rock mass)

In Figure 22, the damage survey of the system support state in the postponed polygon is observed at the production level.

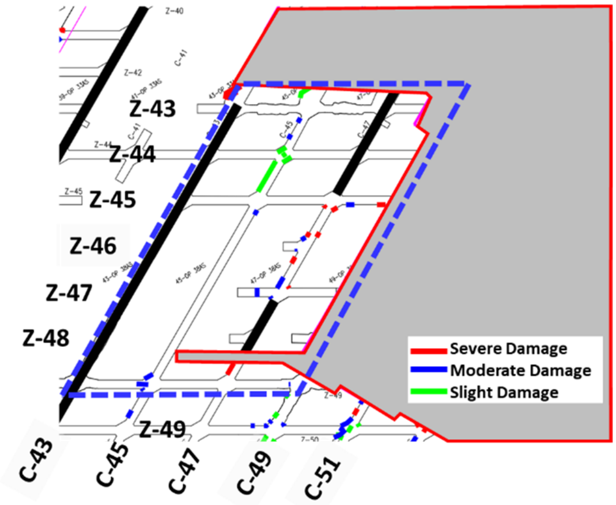


Figure 22 Geomechanical damage survey at production level.

4.4 Hydraulic Fracturing (HF)

Another relevant item that must be considered in the geomechanical analysis of a sector postponed due to seismicity is related to the HF. The FH is implemented above the undercut level and below the production level at a distance greater than or equal to 70 meters ahead of the caving front. For the postponed polygon, the FH was implemented during the years 2017 and 2019 above the UCL and below the production level respectively, with the HF above the UCL campaign covering a larger volume of rock mass compared to the FH below the PL. According to historical records of propagation pressures, the values of these pressures recorded above the UCL are defined as moderate, and those recorded below the production level are defined as high.

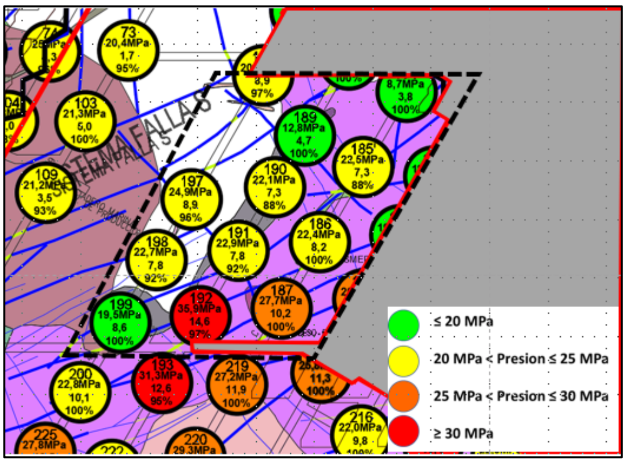


Figure 23 Propagation pressures of HF above UCL.

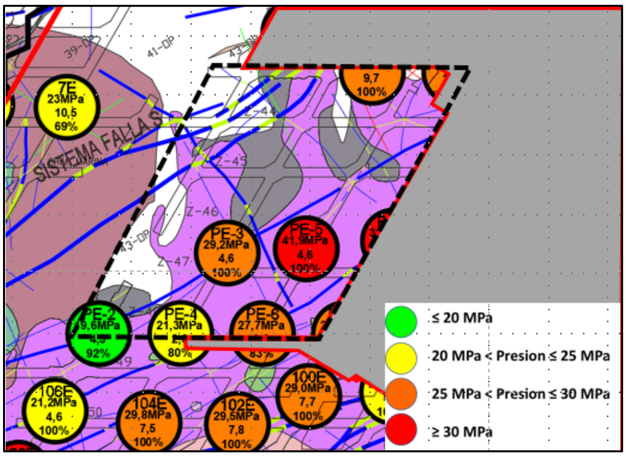


Figure 24 Propagation pressures of HF below production level.

4.5 Conclusions

From the above, regarding the mining activities conducted in the sector, as defined during the year 2016 when the undeveloped area was postponed, the southward expansion of Bloque-2 was carried out with a 150 meter wide caving front. Extraction heights immediately adjacent to the postponed polygon ranged between 35 and 98 meters from a primary rock column of 150 meters. In terms of the seismicity recorded in the postponed polygon, it is noteworthy that both the magnitude and energy of seismic events localized in this sector have decreased. Table 3 show this record. Another seismic parameter analyzed is the Energy Index, which has shown a clear decrease in its values from medium-high to low values during the period 2018-2021. Damage surveys indicate a favorable damage condition for entering the sector to carry out the pending developments because the level of damage recorded is feasible to repair with typical system support (Bolt-Mesh-Shotcrete). Another relevant aspect is the Hydraulic Fracturing conducted in the sector, where propagation pressures above the UCL and below the production level are in the medium range, ranging from 20 MPa to 30 MPa.

Table 3 Magnitude and energy of seismic events

Date	Magnitude	Energy (J)	Heigh (m)
28-12-2015	1.3	3,2 x 10^5	2202
17-01-2016	1.6	3,5 x 10^5	2184
17-03-2016	1.6	8,5 x 10^5	2188
30-07-2016	1.5	1,1 x 10^6	2180
31-07-2016	1.7	2,5 x 10^6	2190
10-03-2018	1.7	3.2 x 10^6	2267
25-09-2018	1.0	6.6 x 10^4	2191
18-05-2019	1.0	1.3 x 10^5	2190
01-07-2019	1.0	7.6 x 10^4	2192
29-03-2020	1.0	7.8 x 10^3	2280
30-08-2021	0.9	4,9 x 10^3	2188

The backgrounds allow us to conclude that the mining carried out to the south, adjacent to the postponed polygon, has generated a favorable geomechanical environment for the completion of the developments in the sector and the subsequent incorporation of this polygon area, allowing the generation of a front width of 210 meters.

5 GEOMECHANICAL GUIDELINES FOR DEVELOPMENTS THE POSTPONED POLYGON

The geomechanical guidelines defined for the execution of the developments were as follows:

- Stop extraction at C-49.
- Stop extraction at breakage points in C-51 western side.
- Reduce extraction by 50% at breakage drawpoints on the eastern side of C-51.
- Isolation of a 3-hour radius of 50 meters for development blasts.
- Simultaneous distant development blasts within a 30-meter radius.
- Following the development blast, commencement of fortification process within a maximum of 24 hours, with a timeframe of 48 hours for completion.
- The recommended fortification for this sector corresponds to the current standard of the support system, that is, Bolt-Mesh-Shotcrete, Cables at Intersections, Drawpoints Steel Arc and Concrete wall whit cables and claps.
- Application of seismic control polygon and the General Procedure for Controlling Seismic Effects in the Mining of Primary Rock in El Teniente Mine.

The developments and constructions of the postponed polygon began during the month of June 2022 and ended 5 months later, in November of the same year. During the development of this sector, no seismicity above magnitude 0.0 was recorded.

6 DRAWBELL COMMISSIONING IN THE POSTPONED POLYGON

The drawbell mining into the postponed polygon (8 drawbells), was conducted from December 2022 to June 2023. During this process, the post-blast seismicity record is presented in Table 4.

Table 4 Post blast seismicity records

Date	Magnitude	Energy (J)	Height (m)
27-12-2022 2° Stage Drawbell Z-47 C-47/49	1.4	3,2 x 10^5	2202
31-12-2022 3° Stage Drawbell Z-47 C-47/49	1.2	3,5 x 10^5	2184
31-01-2023 3° Stage Drawbell Z-46 C-47/49	0,7	8,5 x 10^5	2188
18-04-2023 3° Stage Drawbell Z-48 C-45/47	1.6	1,1 x 10^6	2180

This seismic response did not result in any damages in the surroundings and was recorded during the isolation of each blast. The plan location of each recorded seismic event is show in Figure 25.

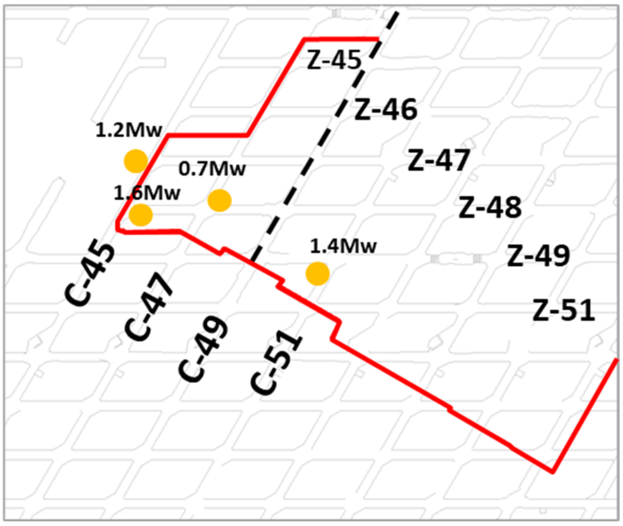


Figure 25 Plan view of the location of post-blast seismic events during the drawbell mining in the postponed polygon.

6.1 Caving Monitoring

With the aim of monitoring this cavity, a borehole was developed to inspect the evolution of the rock mass fracture in height and ensure the propagation of caving. Figure 26 illustrates the design of the borehole around the postponed polygon.

The initial condition or baseline of the borehole is show in Figure 27 dated March 11, 2022, and in Figure 28, the evidence of monitoring using a borehole camera conducted on April 6, 2023, is shown, after the completion of the mining of the 4 drawbells between C-47 and C-49, that is, halfway drawbells of the postponed polygon. Finally, in Figure 29, an image is presented showing the seismic response in the growth area of the postponed polygon associated with the extraction of drawbells.

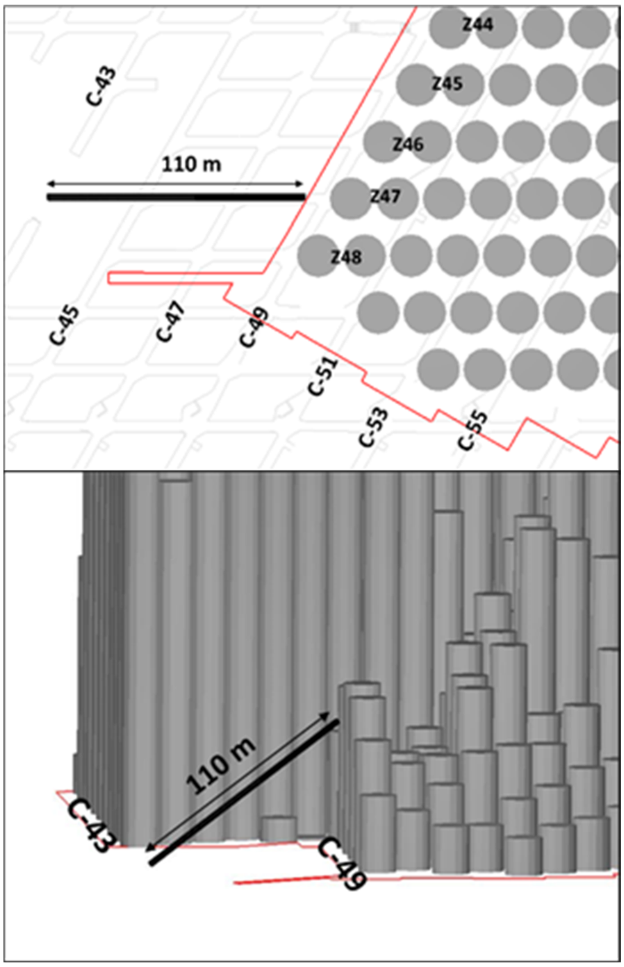


Figure 26 Cavity monitoring borehole.

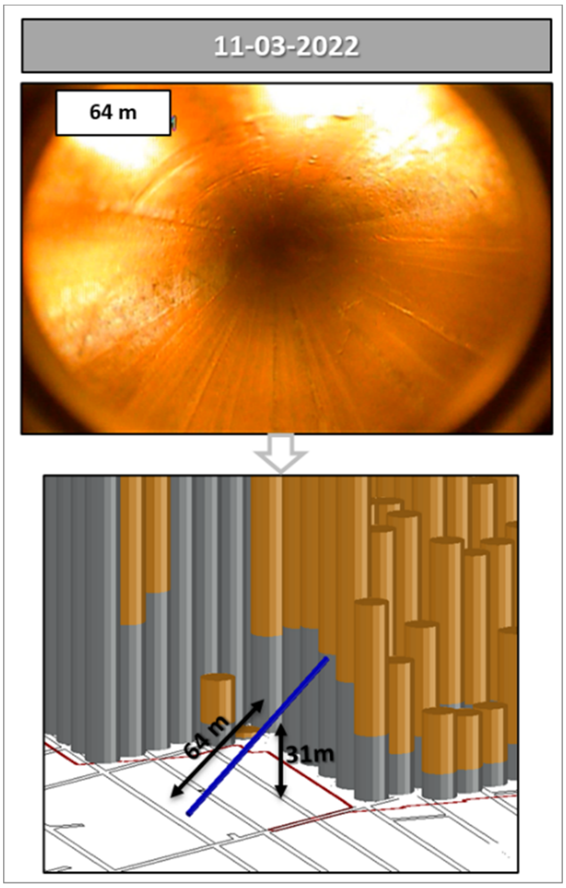


Figure 27 Base line of monitoring borehole.

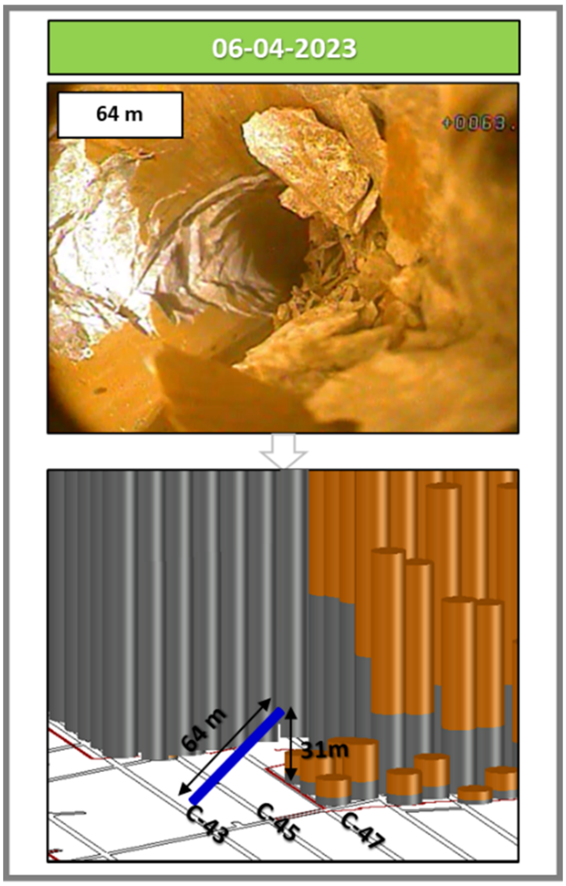
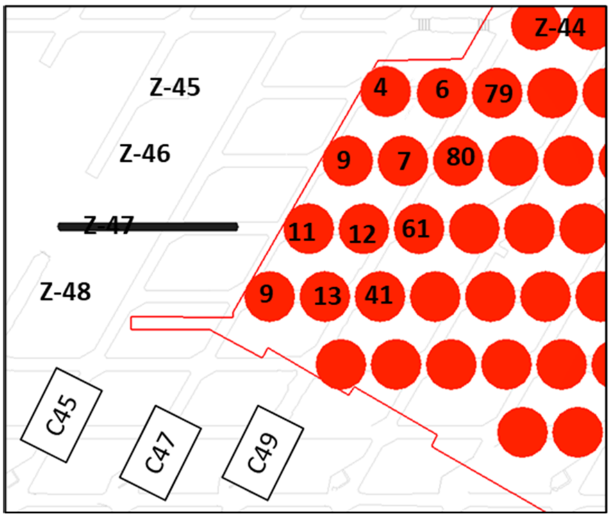


Figure 28 Evidence of caving propagation.



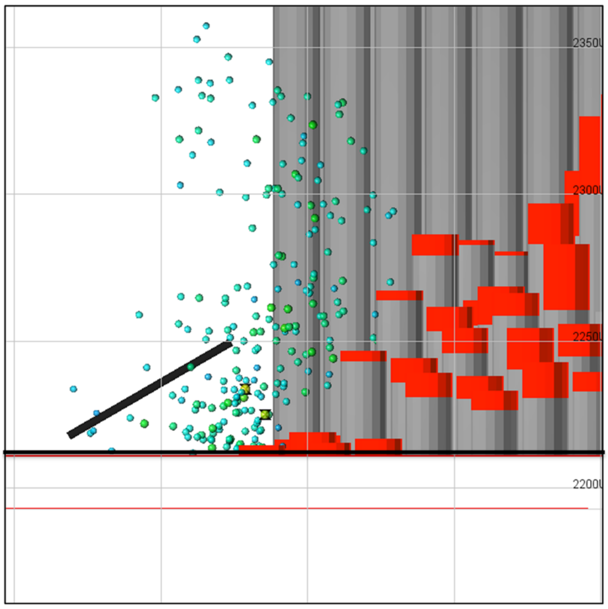


Figure 29 Seismic evidence of caving propagation.

7 CAVING PROPAGATION BLOQUE-2

7.1 Seismic Frequency

The seismic response associated with the new width of the front can be differentiated into three stages. The first of these occurred during July 2023, reaching a peak seismicity of 200 events/day. The second peak of seismicity was recorded during September 2023, reaching a maximum frequency of 100 events/day. Finally, the last peak of seismicity in Bloque-2 corresponds to a quantity of 600 events/day recorded during February 2024.

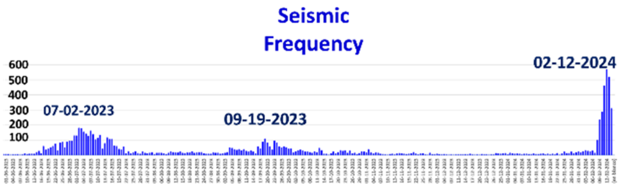


Figure 29 Seismic frequency in Bloque-2.

It is relevant to mention that prior to the first peak of seismic activity recorded in Bloque-2, the seismic frequency had an average behavior around 50 events/day. Therefore, the seismicity peaks recorded correspond to significant changes in the height fracture of the rock mass in response to the geometric modification of the mining width in this productive sector.

The width of the cave front and breakage front during the period preceding the first peak was characterized by an increase from a width of 150 meters for both fronts to a geometry of 180 meters for the cave front and 150 meters for the breakage front. This geometry is observed in Figure 30.

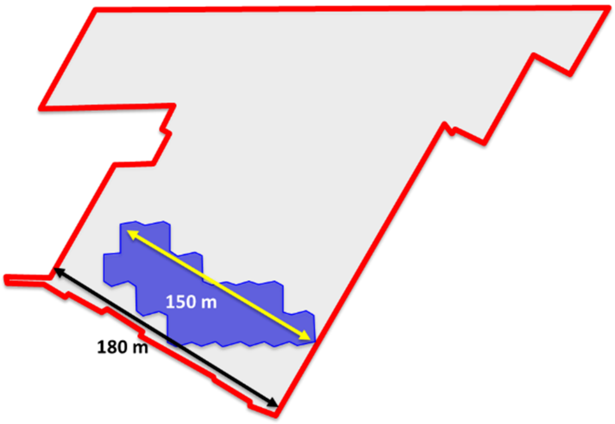


Figure 30 Width front previous first seismicity peak.

The first peak recorded during July 2023 corresponds to a geometry of a cave front width of 210 meters and a breakage front width of 180 meters, as observed in Figure 31. For the second peak, the geometric configuration corresponds to a width of 210 meters for both fronts, as shown in Figure 32, where it is also possible to observe a geometric irregularity in the central area of the breakage front. Once the geometry of the breakage front is regularized and through continuous extraction, the third peak of seismicity is characterized by a width of 210 meters for both fronts, as observed in Figure 33.

The seismic response of the three peaks recorded during the geometric modification of the Bloque-2 face when incorporating the trays of the postponed polygon is observed in Figures 34, 35, and 36 respectively.

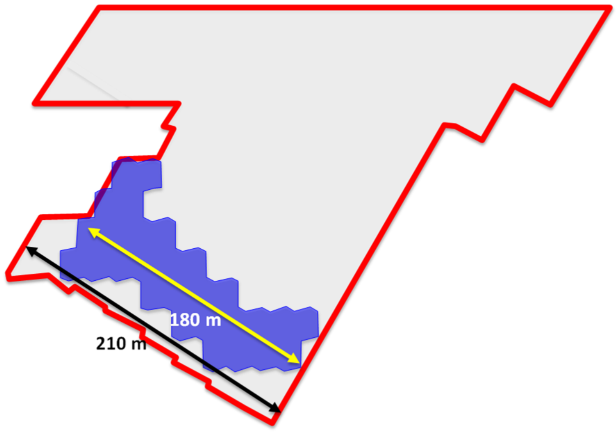


Figure 31 Width front first seismicity peak.

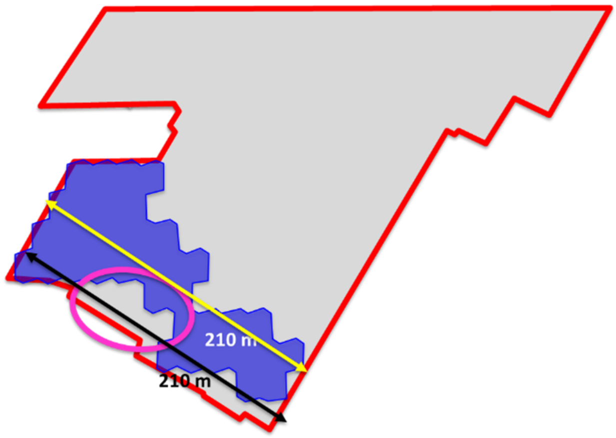


Figure 32 Width front second seismicity peak.

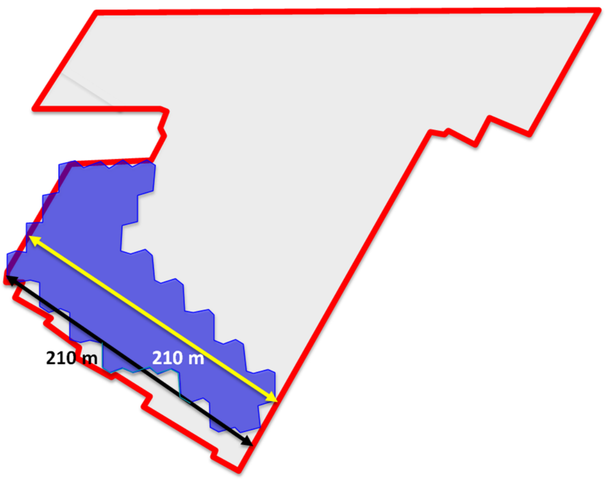


Figure 33 Width front third seismicity peak.

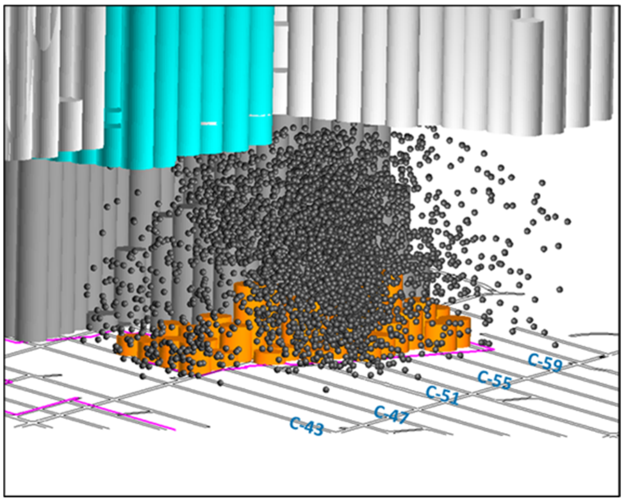


Figure 34 Width front first seismicity peak.

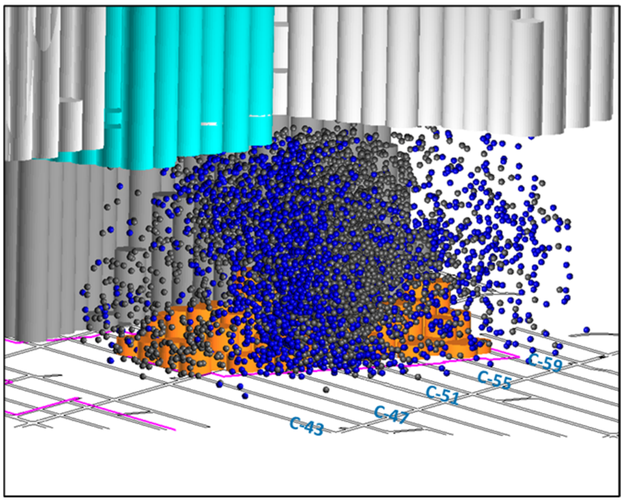


Figure 35 Width front second seismicity peak.

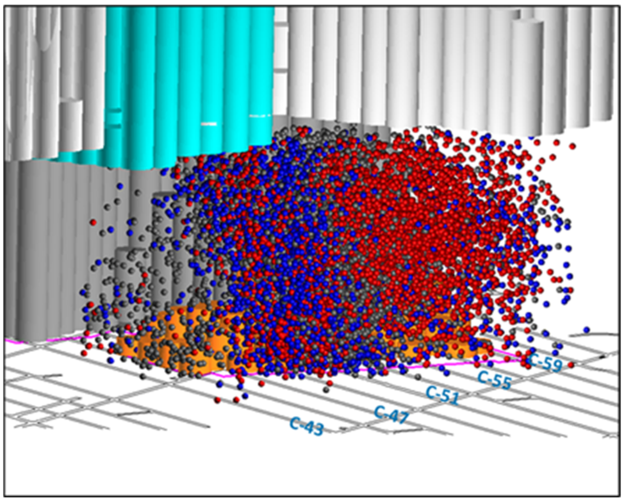


Figure 36 Width front third seismicity peak.

Finally, a plant with the seismicity recorded during the month of February is show in Figure 37, where it can be observed that the seismicity record is located across the entire subsidence front. On the other hand, in Figure Y, it is possible to observe a perspective view showing the upper sunk level, the extraction heights of Block-2, and the seismic response of the third peak recorded. The magnitudes associated with the seismic events of this peak are less than 0.7 ML.

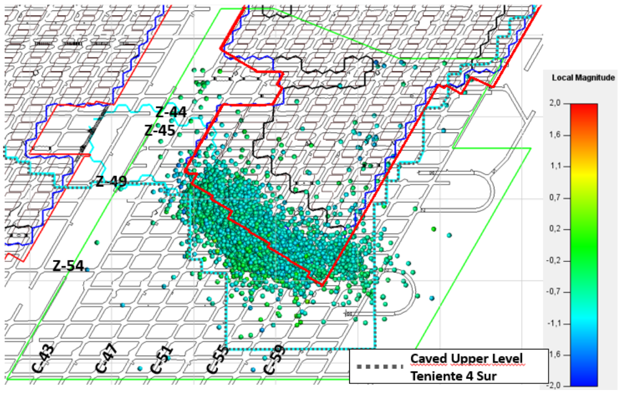


Figure 37 Width front third seismicity peak.

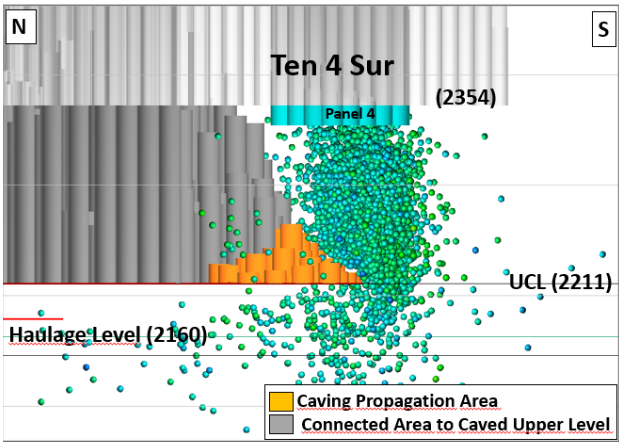


Figure 38 Width front third seismicity peak.

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