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Assessing the cave mining collapse process of Recursos Norte project at El Teniente mine

D. Garcés, C. Lobiano, R. Andrades and F. Hidalgo
Codelco-El Teniente, Rancagua, Chile

ABSTRACT

Recursos Norte mine is an expansion project of *Reservas Norte* and *Dacita* mines, aiming to provide 195 million tons of reserves at an average grade of 0.75% to the northern part of the *El Teniente* mine. *Recursos Norte* is a post undercutting panel caving operation that uses hydraulic fracturing in order to mitigate the seismic responses during cave growth. The lithology primarily comprises the *El Teniente* mafic complex with the intrusion of dacite porphyries in the central part of the orebody, indicating a competent rock mass with low porosity and permeability. However, the main faults system has played a significant role in opening sealed stockworks as mining progresses northward, where deformation rates increase with the abutment stress, initiating a collapse process in the eastern part of both production and undercut levels.

This article provides the main elements that describe the operational strategy to manage the collapse process at the *Recursos Norte* mine. Such conditions required additional rock support design, intensive extraction rates, comprehensive geomechanical analysis, new approaches for drilling and blasting, and cave growth sequencing. Ultimately, the analysis of conditions before and after implementing this risk mitigation strategy is discussed, highlighting the success in ensuring the continuity of operations for this mining project.

1 INTRODUCTION

Recursos Norte mine is located in a massive copper porphyry deposit on the northern boundary of Reservas Norte and Dacita mines, designed to provide continuity to the caving process and recover the northwestern part of the El Teniente orebody. Post undercutting with the application of hydraulic fracturing (above the undercut level and below the extraction level) is used as the caving method for Recursos Norte in order to mitigate the seismic hazard during its operation. The undercut level is at 2,120 m elevation, approximately 18 meters above the extraction level. The range of planned draw heights is between 60 (western side) to 420 m (eastern side), with an average of 285 m. The project covers a total mining area of 342,000 m^2 with 195 million tons of reserves at an average grade of 0.75%, and mining rates of 35,000 tpd are expected during the steady-state regime.

Over 60,000 m^2 of undercutting area has been incorporated into extraction since the cave establishment began with the first blast (drawbell and undercutting) in August 2019, reaching a caving front of 550m approximately, and allowing the mine to reach production rates of 15,000 tpd to date. Figure 1 shows an isometric view of Recursos Norte mine in relation to other mine footprints at El Teniente mine.

This article outlines the operational strategy implemented in the Recursos Norte mine to deal with a collapse process in both undercut and extraction levels. Rock support design, intensive extraction rates, and new approaches for drilling are described as main elements successfully applied to ensure the operational continuity of the project.

2 MINE BACKGROUND

2.1 Geology

Recursos Norte mine is situated entirely in a primary rock mass, with the El Teniente mafic complex (CMET) serving as the predominant lithology for the mineralization. Within the layout, the presence of dacite porphyry (DP) is identified in the central area, extending roughly in a north-south direction throughout the project. These lithologies are characterized as competent in situ rock mass, with low porosity and permeability, and filled stockworks and veins.

Geological mapping is carried out for every tunnel advance during the mine development process, where four main geological fault systems are identified for the mine. A plan view of the lithologies and structural faults is shown in Figure 2, illustrating the complexity of the geomechanical conditions at Recursos Norte mine.

The area of interest shown in Figure 2 is mainly located in CMET lithology, without the presence of significant lithological contacts; however, a main geological structure (i.e., the N3 fault) is observed in this area. The N3 fault is considered the most important geological structure, as described in Table 1. This discontinuity has been mapped in all four mine levels (i.e., undercut, extraction, intermediate haulage, and ventilation levels) compared to the others, reaching an extension of 750 m and a striking roughly in a northeast direction; therefore, N3 fault is categorized as the only second-order fracture according to Pusch (1994). In general terms, the N3 fault has an average thickness of 1.1 cm and is filled with a mix of gypsum- anhydrite- molybdenite-quartz-chlorite minerals.

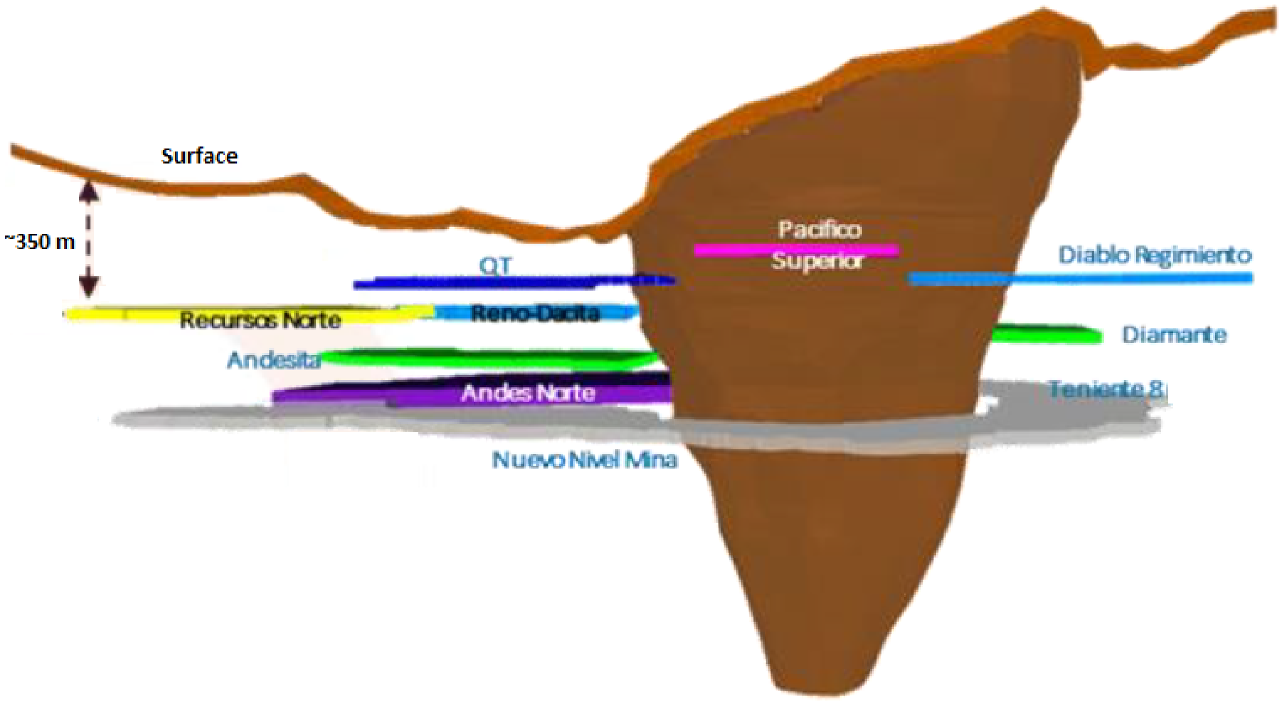


Figure 1 Isometric view of El Teniente mine footprints indicating the location of Recursos Norte mine.

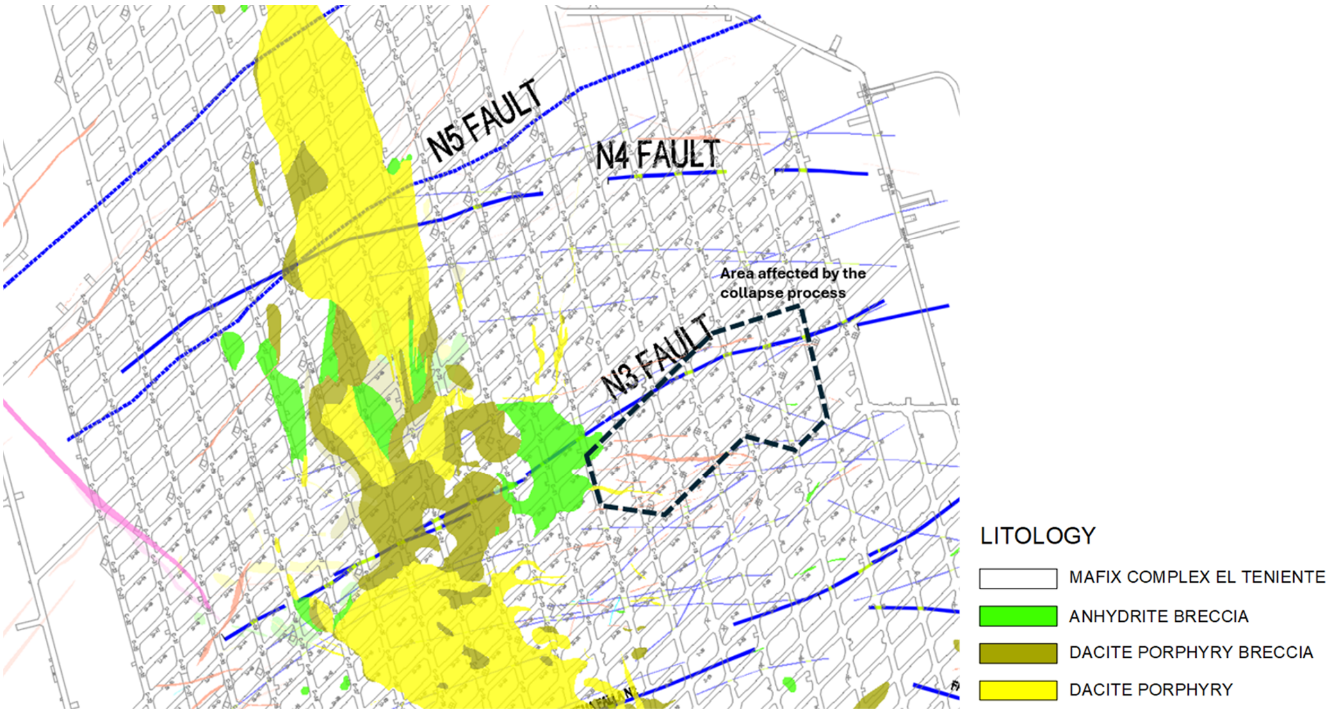


Figure 2 Plan view of the lithologies and geological structures for Recursos Norte mine.

Table 1 Summary of main geological structures observed during the development of *Recursos Norte* mine

Fault	Persistence (m)	Average thickness (m)	Strike	Dip
N3	750	1.1	N56°E	84°NW
N4	122	0.7	N85°E	74°SE
N5	470	0.9	N66°E	83°SE

2.2 Rock mass conditions

Based on the lithological model, geological fault system and ore fragmentation at drawpoints, Brzovic and Schechter (2013) proposed a geotechnical zoning that indicates the rock mass cavability of primary rock at El Teniente mine (Figure 3). Table 2 summarizes the classification of the rock mass according to the geotechnical zoning.

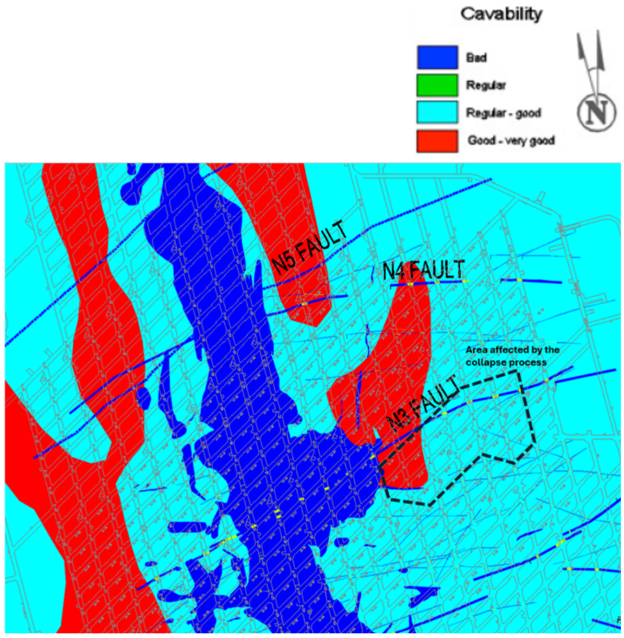


Figure 3 Plan view of geotechnical zones indicating the rock mass cavability expected in the study area (modified from Garces et al., 2020).

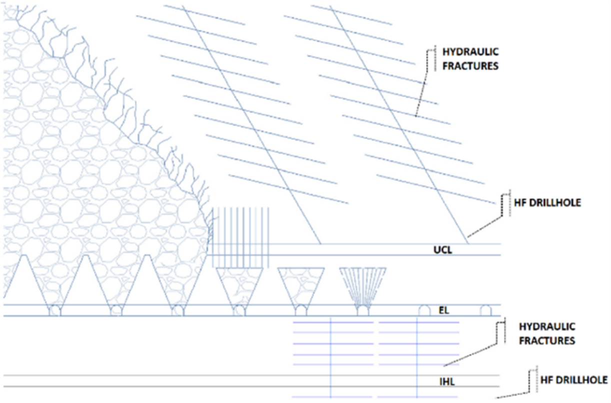
Table 3 Main rock mass properties for the geotechnical zones

Cavability	UCS (MPa)	GSI	E (GPa)
Bad	140	85	40
Regular	150	85	48
Regular-good	130	75	57
Good-very good	110	70	55

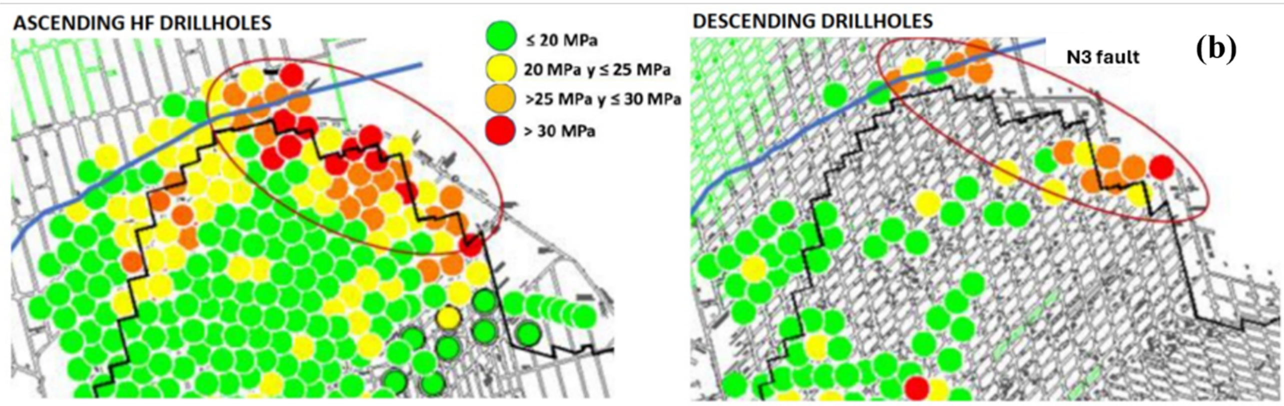
The area of interest is mainly located between regular and good zones, which is classified for cavability as regular-favorable and favorable-very favorable due to the increase of veins frequency in the surrounding area.

2.3 Mining method

Recursos Norte mine implemented the use of post-undercutting panel caving with hydraulic fracturing. This mining method offers an increased operational flexibility through the post-cut sequence, and also, contributes to mitigating the seismic hazard during mine operating (Figure 4a).



(a)



(b)

Figure 4 (a) Post undercutting (or conventional) panel caving with hydraulic fracturing (modified from Pardo and Rojas, 2016), and (b) hydraulic fracturing pressures above the undercut level and below the extraction level.

Figure 4b shows the hydraulic fracturing data between 2014 and 2022, where two types of fracturing were performed: (i) hydraulic fracturing upwards the undercut level with a length of 100 m and a radius of 20 m, and (ii) hydraulic fracturing beneath the extraction level with a length of 70 m and radius of 20 m. High pressures are notably observed in the eastern part of the layout (above 25 Mpa), which is due to both the end cave line effect (no further cave establishment) and large lags in the undercut level (above 40 m).

2.4 Mine design

In terms of mine design, the Recursos Norte project considered four main levels to properly initiate the planned production: undercut, extraction, intermediate haulage, and ventilation levels. Figure 5 describes the elevation and drift section of each level. It is important to note that the main haulage level, known as Teniente 8, is excluded from this illustration since it is employed for the overall production at El Teniente mine.

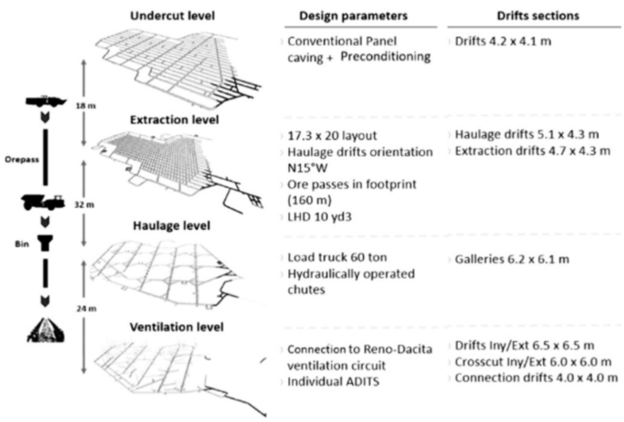


Figure 5 **Mine design applied to Recursos Norte mine (modified from Fernández et al., 2020).**

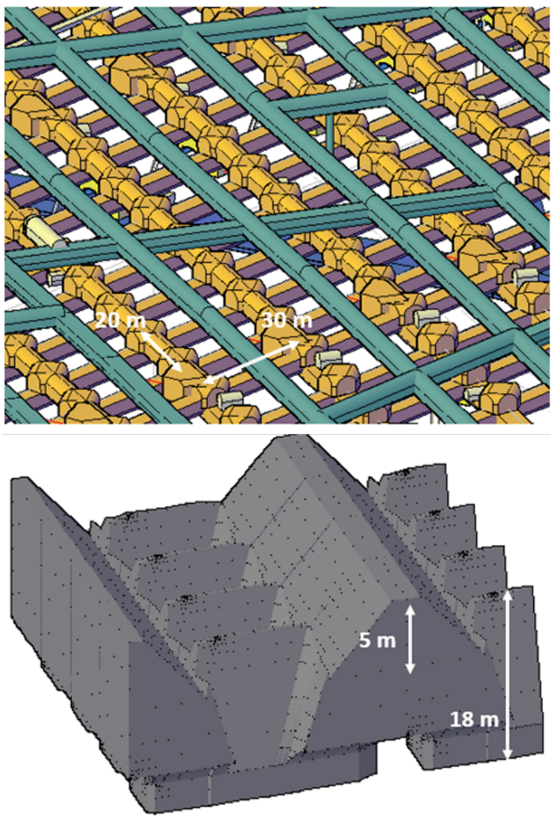


Figure 6 **Extraction level layout and pillar dimensions in Recursos Norte mine.**

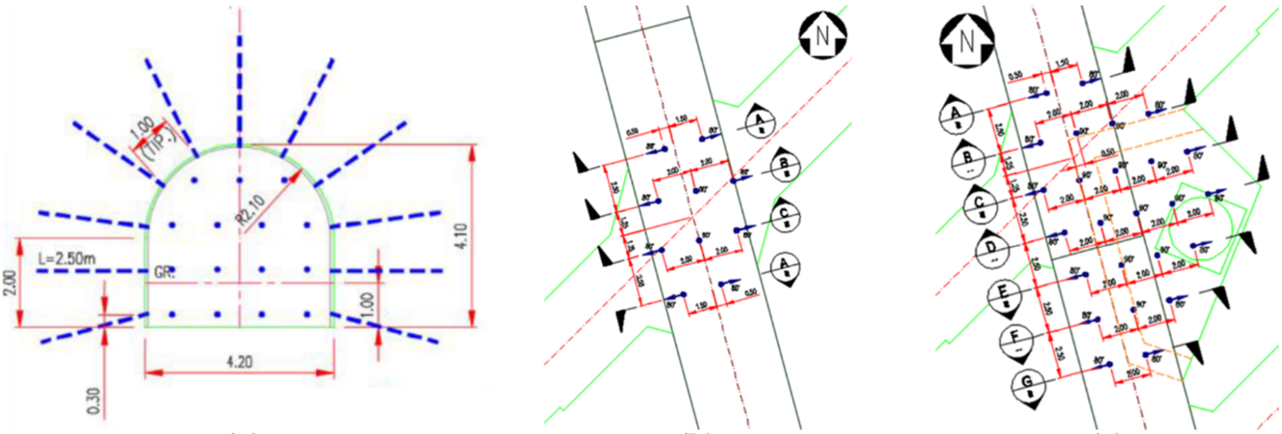
In addition, a 30 m x 20 m El Teniente layout was developed in Recursos Norte mine in order to maintain the same mine design as previously implemented for Dacita and Reservas Norte mines. Figure 6 schematically depicts the extraction level configuration and pillars dimensions included in the mine design.

2.5 Ground support

Ground support design for Recursos Norte mine is based on rockburst analyses at the El Teniente mine to estimate the energy demands and characterize the elements that compose the system. As a result, ground support accounts for energy dissipation and deformation capacity, as well as corrosion strength, providing a system capable of both retaining and reinforcing (Muñoz et al., 2016).

In general terms, the ground support design for the undercut and extraction levels at Recursos Norte uses the bolt-mesh-shotcrete system throughout the development of drifts. For details on this ground support design, please refer to Figure 7(a). The thickness of the shotcrete is considered as 6 cm in two steps. Initially, a layer of 5 cm is applied as pre-shotcrete, followed by a second layer of 1 cm over the mesh. The second layer of shotcrete is able to protect the mesh from operational damage, prevents a risky condition known as shotcrete rain.

Given the experience in El Teniente mine, a complementary ground support system consists of cable bolting with plate and barrel-wedge installed in both orepass caverns and intersections between drifts (in the extraction level) in order to mitigate the risk of wedge failure and ground fall. Figure 7(b) and Figure 7(c) provide more details on this additional ground support design.



(a) (b) (c)

Figure 7 Ground support design in Recursos Norte mine for (a) undercut and extraction levels, (b) intersections between drifts, and (c) orepass caverns (modified from Celis, 2020).

3 COLLAPSE PROCESS

Over the past years, the El Teniente mine has experienced more than 30 collapses in different sectors (e.g, Esmeralda mine, Reservas Norte mine, and Dacita mine) (Quevedo et al., 2019). Most of these events have been observed in areas surrounding the undercut front, highly affected by the intensity of the abutment stress (Landeros et al., 2012). The remaining collapses have taken place over abandoned orepasses, characterized by structural failures and rock falls from the caverns' sidewalls and roofs.

Collapses at the Recursos Norte mine were noted as the cave front moved towards the N3 fault in the eastern part of the undercut level in August 2022. Since then, the damage has extended over five drifts in both undercut and extraction levels, affecting an approximate area of 8,400 m^2 (Figure 8) throughout six months.

As undercutting advanced toward the fault in the eastern part of the layout, load shedding and damage were observed in the sidewalls and roof of the production level drifts behind the N3 fault. The initial phase of the collapse was marked by shotcrete cracking, progressing to moderate fracturing and bulking, and ultimately leading to the emergence of intense fracturing and convergence of the drifts. It is noteworthy that these deformations occurred gradually over periods of days to weeks, rather than sudden collapses (Figure 9).

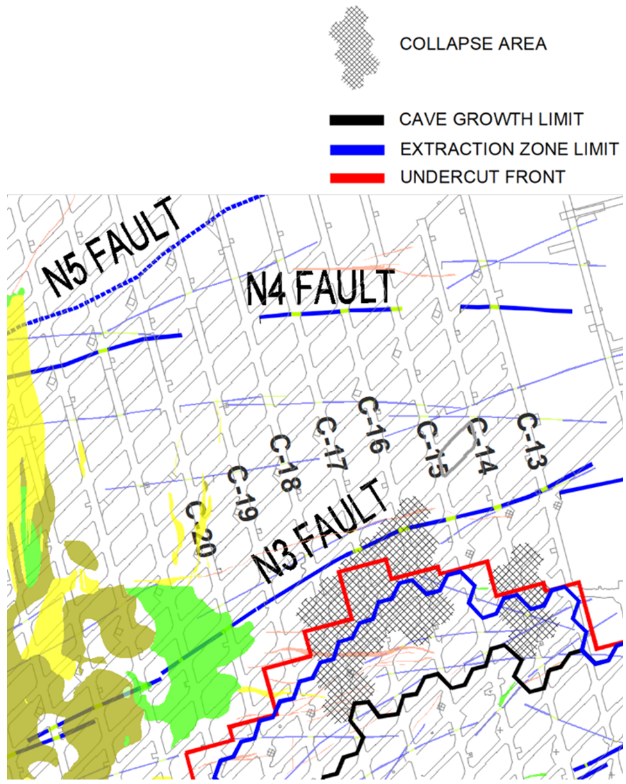


Figure 8 Plan view of the final collapsed zone at Recursos Norte mine.

Figure 9 Sequence of damage observed in the extraction throughout the collapse process.

Although previous mine experience at the El Teniente mine indicates that the occurrence of collapses is associated with wide caving fronts (Araneda and Sougarret, 2008), the initiation of the collapses at the Recursos Norte mine is predominantly attributed to geological conditions and mining-related activities. The main factors that contributed to the occurrence of the collapse are described as follows.

- The development of a slab effect (i.e., large extension of the cave growth area) combined with low draw angles during cave establishment, increasing the abutment stress near the cave front, and thus, inducing a reduction in the friction and cohesion properties of the rock mass (i.e., deconfinement process). Moreover, such conditions may potentially create an uncaved pillar between the existing cave and the new cave during cave establishment (Cuello and Newcombe, 2018).
- An extension of the cave front, spanning approximately 150 meters, remained parallel to the N3 fault for approximately eight months. This circumstance arose from a rockburst at the Recursos Norte mine in September 2021, ceasing cave establishment activities until remedial measures were implemented to address the damages and optimize draw angles (between 30° to 35°).
- The reduction of the pillar dimensions for orepass as a consequence of overbreak during the development of the extraction level (not discussed in this article).

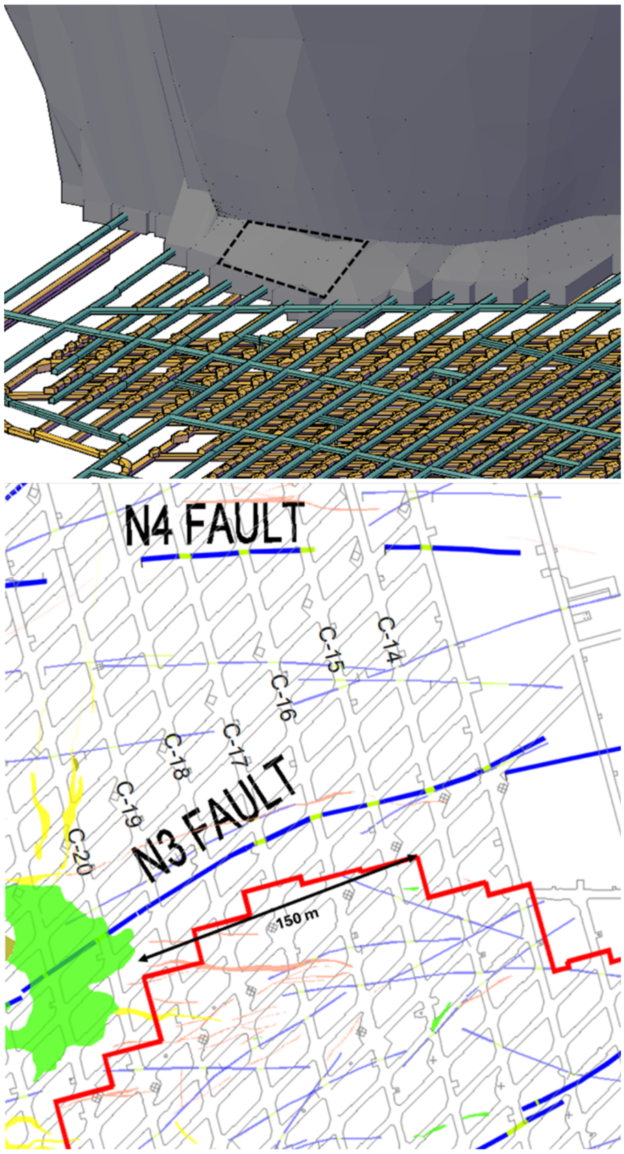


Figure 10 (a) Cave back geometry of the area before the collapse process, and (b) Location of the cave line compared with the N3 fault.

4 STRATEGIES FOR ASSESSING A CAVING COLLAPSE – THE RECURSOS NORTE MINE EXPERIENCE

The development of the mining strategy aimed to define a methodology not only to sustain operational continuity of the mine, but also to restore the undercutting front around the collapsed area. The strategy is divided into three main categories, namely extraction, ground support, and drill and blast approaches.

4.1 Extraction strategy

In general terms, the extraction strategy was designed to prevent the continuous spread of the collapse to the undercut and extraction levels. This strategy involved drawing ore at high rates to match the extraction ellipsoids between drawpoints in the surrounding collapsed area, thereby eliminating residual pillars in the undercut level (decreasing induced stress in the extraction level).

Initially, the extraction strategy prioritized higher draw rates for drawpoints with lower draw heights in order to foster regular cave back development in the area. Fragmentation of caved material was regularly monitored as a component of the ground control aspect of the strategy, as depicted in Figure 11a. As the collapse advanced in a westward direction and draw heights increased in proximity to the cave front, draw rates were weekly adjusted to deal with new mine and seismicity conditions. Towards the latter stages of the strategy, draw rates were reduced in drawpoints adjacent to the cave front, and the observed fragmentation experienced a diminishing trend at higher draw heights (Figure 11b).

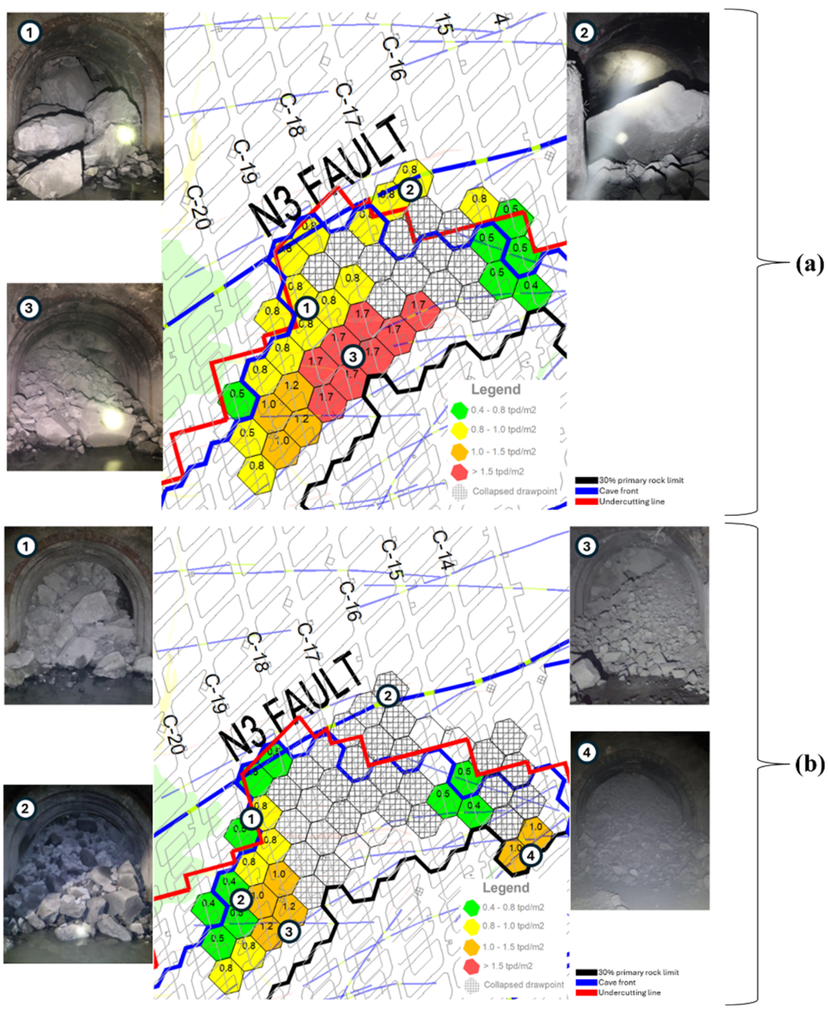


Figure 11 Polygon of the extraction strategy around the collapsed area (measured in tpd/m2) and fragmentation control. (a) Definition of initial draw rates, and (b) final draw rates of the strategy.

The extraction strategy facilitated the cave back in reaching draw angles between 30° and 45° in the vicinity of the collapse area (Figure 12). This cave geometry effectively minimized the occurrence of damaging seismic events and ceased the northward propagation of collapse, particularly within the undercut level. Consequently, these circumstances facilitated the resumption of cave establishment in this part of *Recursos Norte* mine.

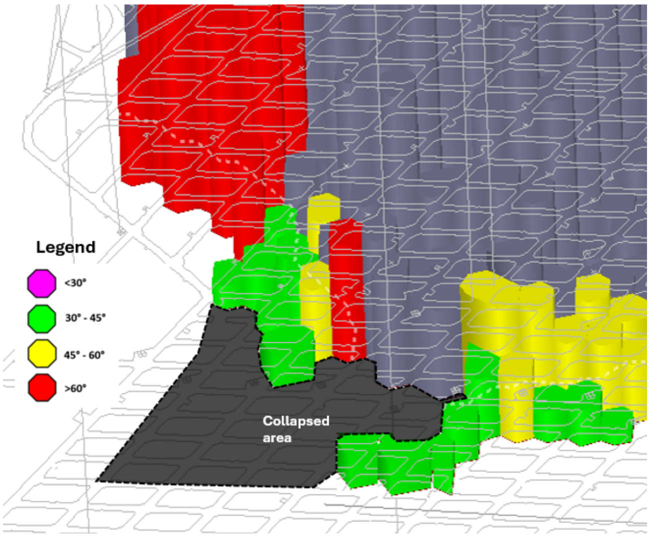


Figure 12 Final draw angles in the area around the collapse at Recursos Norte mine.

4.2 Ground support strategy

The ground support strategy consisted of installing additional support and filling collapsed drifts. These activities were carried out in parallel with the extraction strategy in order to help confine and provide more stability to the area affected by the collapse process. Figure 13 illustrates the location of each type of ground support in the collapse area.

Concrete was used to fill collapsed drifts unable to rehabilitate, generating macro pillars between undercut and extraction levels. On the other hand, concrete and steel arches were installed as reinforcement in two extraction drive (C13 and C15) to maintain the mine route to the production area. The extension of this type of support is roughly 80 m. To date, these drifts have not been affected by a collapse process.

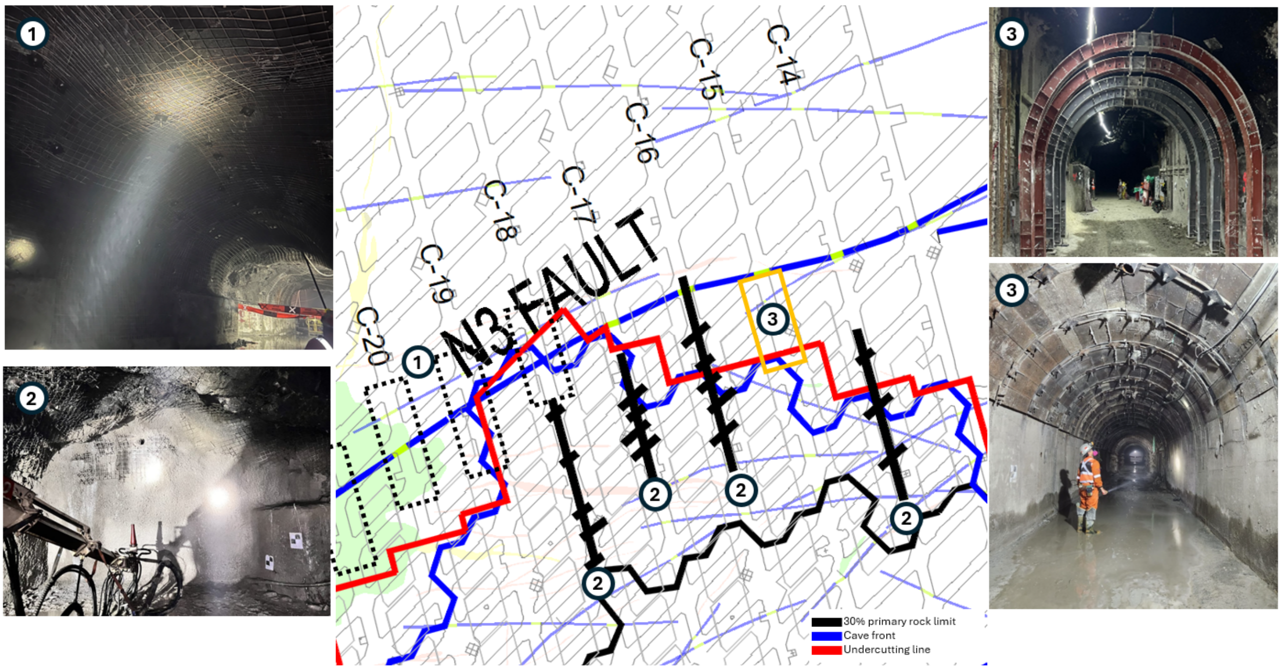


Figure 13 Plan view with the location of each type on ground support to reinforce the collapse area.

Finally, additional ground support was installed in western drifts to avoid the spread of the collapse process when cave establishment approaches the N3 fault. This system is composed of double cablebolt – electro welded mesh – friction bolt (split set) as the second layer to increase strenght and dissipation capacity.

4.3 Drilling strategy

The objective of drilling designs is to recover the undercutting front from the extraction level. This strategy allowed the drilling successfully reaching zones that were not possible to access in the undercut level, and thus, providing the geometry of the crown pillar at the front of the collapse area. Drilling of slots is included in the design through the use of inclined drillholes that connected in the center of the drawbell. A key aspect took into account during drilling and blasting was removing any remaining pillars located between the undercut drift and the edges of drawbells (i.e., the minor apex) (Rivera et al., 2016). Figure 14a illustrates a longitudinal section of the drilling design applied from the extraction level.

However, a special drilling design was developed in cases where drawbells were already blasted before the collapse initiation. This design considered drilling from the adjacent undercut drift in direction to the potential pillar remained from the collapse using drill rings with different angles and lengths as depicted in Figure 14b.

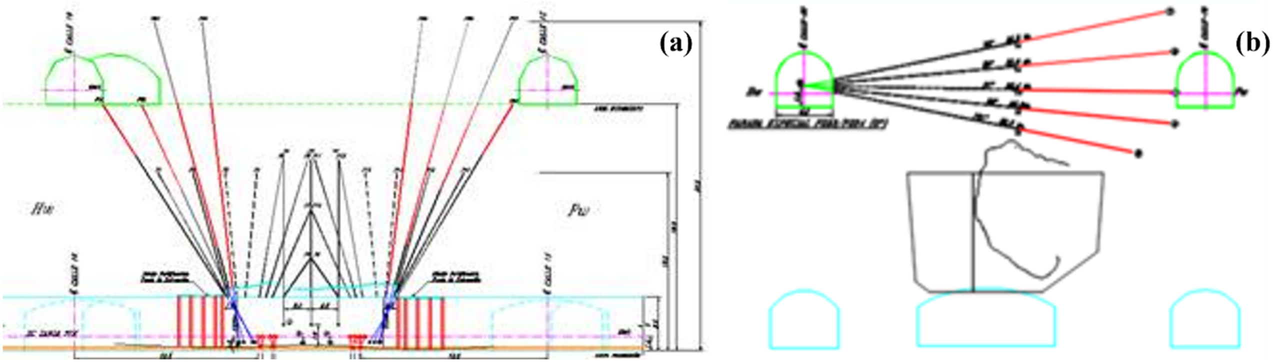


Figure 14 Drilling design of drawbells applied to (a) the extraction level, and (b) the undercut level (modified from Atala 2022).

5 CONCLUSIONS

The successful management of the collapse process at the Recursos Norte mine ensured operational continuity by strategically preventing the formation of remnant pillars above crown pillars, controlling the extent of damage at the extraction level, and restoring the undercutting front around the conventional panel caving area. The adoption of this integrated strategy underscores the experience and knowledge gained from past collapses at the El Teniente mine, providing effective operational approaches.

The implementation of extraction rate strategies, reinforced ground support measures, and innovative drilling designs has mitigated the potential for a more extensive mine collapse. This collaborative approach not only addressed immediate damages but also reinforced the long-term stability of the mining operation, thereby ensuring the safety of mine workers and critical production infrastructure. Such a successful approach highlights the importance of interdisciplinary collaboration and the continuous search for best practices in cave mining operations. Ultimately, these experiences serve as valuable lessons for future mining projects to ensure the sustainability and safety of mining operations.

Even though this article focused on a strategy to address a cave mine collapse, the following are a few lessons learned in this experience.

- Thoroughly analyze the combined effect of wide cave fronts, presence of main geological structures and sub parallelism of the undercut front to geological structures during cave growth and operation. Developing early plans to face mine contingencies, such as collapses, are key to reducing their impact, deliver suitable results, and provide production continuity in cave mines.

- Control of the drill and blast and the extraction (e.g., draw angles) processes to ensure that no remnant pillars are left between the undercut and extraction levels. Remnant pillars combined with the abutment stress ahead of the undercut line directly increase the risk of generating a collapse in the surrounding area.
- Quality assurance and control during mine development are essential for providing stability. Over excavation, especially during the construction of ore passes, is detrimental to the crown pillar strength.

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