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Lessons learned during initial slot blasting in Chuquicamata underground mine

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ABSTRACT

Undercut blasting is one of the most important events during the life of an underground caving mine. The main objective of this process is to induce the caving propagation by cutting the lower part of the rock mass. This process requires a free face available that provides the rock with room to expand when is blasted and is the starting point of the breakage and caving. This free face can be achieved by creating a boundary weakening space through the access drift in the undercut level by drilling and blasting where the space created will serve as volume reception from the undercut ring blasting. The Chuquicamata Underground Mine, one of the most important underground operations have implemented various drill & blasting designs during the life of the project to face the different conditions presented during the operation, always looking for the design optimization, increasing productivity and reducing costs. Part of the continuous improvement was to find the best strategy for the slot blasting for the new macro-blocks, South and North following the lessons learned from the initial slot blasting in the Central macro-blocks. This document compiles 4 years of information about slot blasting and shows the new strategy implemented which increased the development rate of the slot in the undercut level by opening the free face in multiple sectors reducing the cycle time and ramp-up time. All the lessons learned provide the information to face the initial slot blasting for the next 12 macroblocks planned for the first level.

1 INTRODUCTION

A crucial part of the life of any mining operation is the opening of the free face to generate sufficient room and space for the movement of the fragmented ore after blasting. The strategy for generating the free face will depend on the underground exploitation method, the type of blasting and its design. However, most blasting strategies associated with the free face blasting consider the initial opening or blasting from a larger diameter raise, which can be carried out by drilling and blasting or mechanized, where blastholes are drilled around it depending on the geometry required and the available volume for receiving the blasted mineral.

Inefficient slot openings can lead to ore loss, delays in production, re-slotting or re-drilling. Conversely, slots which are opened quickly and efficiently allow immediate access to ore, additional access to headings, and high production rates (Bull & Page, 2000).

The main objective of this type of blasting is to open a free face with sufficient space or volume to begin production blasting. In mining methods by Sublevel Stoping, the first stage is to create a slot between the vertical horizons defining the planned stope. This is achieved by enlarging a suitably located raise or long-hole winze (LHW). The slot is created as an expansion void into which the remainder of the stope is formed by the sequential blasting of production holes. In most cases, the production holes are drilled in rings parallel to the orebody dip between the drilling drives. Mining proceeds through the sequential firing of production rings into the advancing void with the broken ore being recovered from a specific extraction horizon (Villaescusa, 2014).

In the Sublevel Caving (SLC) method, the general process of slot opening drifts is described in technical papers about the mining method (Bull & Page, 2000; Di Giovinazzo & Singh, 2010, Kosowan, 1999; Power & Just, 2008, Lewis, 2022). Page & Bull, for example, describe in detail 3 slot opening strategies for SLC. The first of these corresponds to a strategy that does not consider a slot drifts that connects with the extraction drifts. A second method where the slot starts at the extreme of the access perpendicular to the extraction drifts by a single slot raise and vertical drillholes are blasted around it and continue to be blasted along the access drift. And finally, methods that do not use a free-facing slot raise, but rather each extraction drift has downturned drillholes that break towards the slot drift using it as a free face.

Lewis (2022) describes different slot opening strategies at the Diavik Diamond mine and the lessons learned. Each strategy is compared in terms of security, ore recovery, and ease of opening. It is concluded that strategies where the opening of the slot drift crosses the extraction drift and then makes the connection between them turned out to be effective and became standard in production areas in the mine.

In the case of Block/Panel Caving mines, authors such as Laubscher (2000) and Brown (2007) suggest the best slot opening location and direction of caving, mentioning the slot opening through the access drift connecting with the undercut drift, but without further details of their application. Engineering firms provide the details of the drilling and blasting design, along with the drilling pattern around the slot raise and slot rings along the access drift. However, detailed information on the process, the strategy to follow and the problems associated with available volume, direction of the slot, interaction with drawbells and how to face intersections is difficult to find.

For its part, the Chuquicamata Underground Mine, in its years of operation, has acquired experience in slot opening, documenting the lessons learned. The objective of this document, therefore, is to show the experience obtained in the Chuquicamata Underground Mine, the methodology used that led to the consolidation of a strategy that increased the slot advancement rate.

2 BACKGROUND

2.1 Chuquicamata Underground Mine

Chuquicamata Underground Mine, located in the Antofagasta Region in northern Chile, arises as a project that seeks to transform the open pit mine with more than 100 years of operation into an underground mine, with the aim of exploiting the resources under the open pit mine. The start-up of the operation begins in 2019, with the goal of reaching a regime of 140 ktpd in a 7-year ramp up and seeking to extend the lifetime of the mine by 40 years.

The exploitation method of the underground mine corresponds to the macroblock caving variant, composed of different exploitation units which work independently. This variant allows the operation to be made more flexible and have productive areas while others are under development or preparation. The method is based on generating a basal cut in each macroblock by drilling and blasting, thus generating the breakage and caving propagation in the rockmass, which descends by gravity towards the drawpoints. There are currently three macroblocks in production: Central, South and North macroblocks, where each unit has approximately 70,000 m^2 (Mühlenbrock et al., 2020).

Owing to the nature of the Chuquicamata Underground Mine, the success of the method requires the continuous opening and construction of the slot so that the caving is intensive in incorporating area and not delaying production plans that alter the business for the company. Unlike other variants of block caving, where the slot opening period is short compared to the period of the undercut blasts, the beginning of each macroblock, which function independently of each other, has allowed Chuquicamata Subterránea to gain experience in a short period of time.

On the other hand, the main reason for slot opening delays is related to the type of strategy chosen that allows correct execution of blasting, in terms of height and available volume. If the slot is not opened correctly, the undercut height of the first undercut radial rings is limited, which are not capable of adequately displacing material as they do not have the needed free face. In these cases, re-drilling must be carried out and special or extra blasting has to be done in order to continue with the incorporation of undercut drifts and the area to be caved. The latter not only involves additional resources, but also rework in areas that present a risk to the operation due to exposure to an already blasted environment.

Given this background, and the lack of documented information about the undercut beginning through slot, in Chuquicamata Underground Mine strategies or methodologies have been proposed in order to evaluate the results and find the most appropriate configuration.

2.2 Undercut slot blasting in Central Macroblocks

The beginning of the undercutting in the Central Macroblocks in the Chuquicamata Underground Mine began from the south side of the macroblock growing towards the northeast with the first blasting carried out on Access Drift 01 corresponding to the first Slot blasting for the opening of the free face along the drift. This would allow the undercut drift to be opened as the intersection of the access drift with the corresponding undercut drift was passed until the midpoint between drifts and with them the incorporation of area.

The project detailed design delivered initial designs for the slot, which corresponded to the drilling patterns around the slot raise and the blast holes along the access drift (see Figure 1 and Figure 2). However, there was no strategy mentioned that would allow facing the intersection areas between drifts, and how to correct the possible problems of volume and tonnage to generate sufficient free face space for each slot blast.

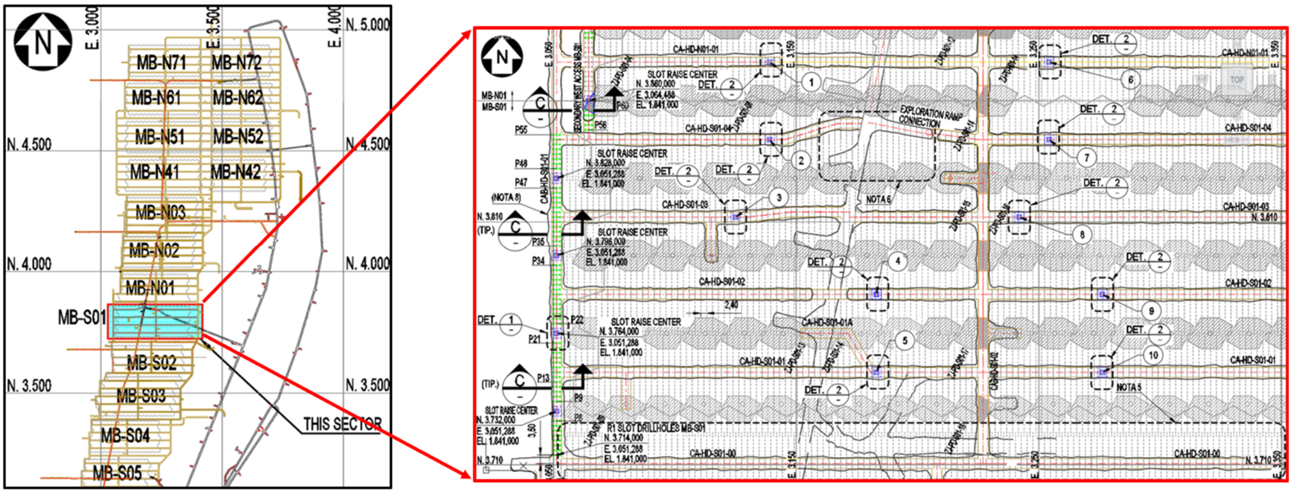


Figure 1 Drill and blast slot design in Central Macroblock – Plan view.

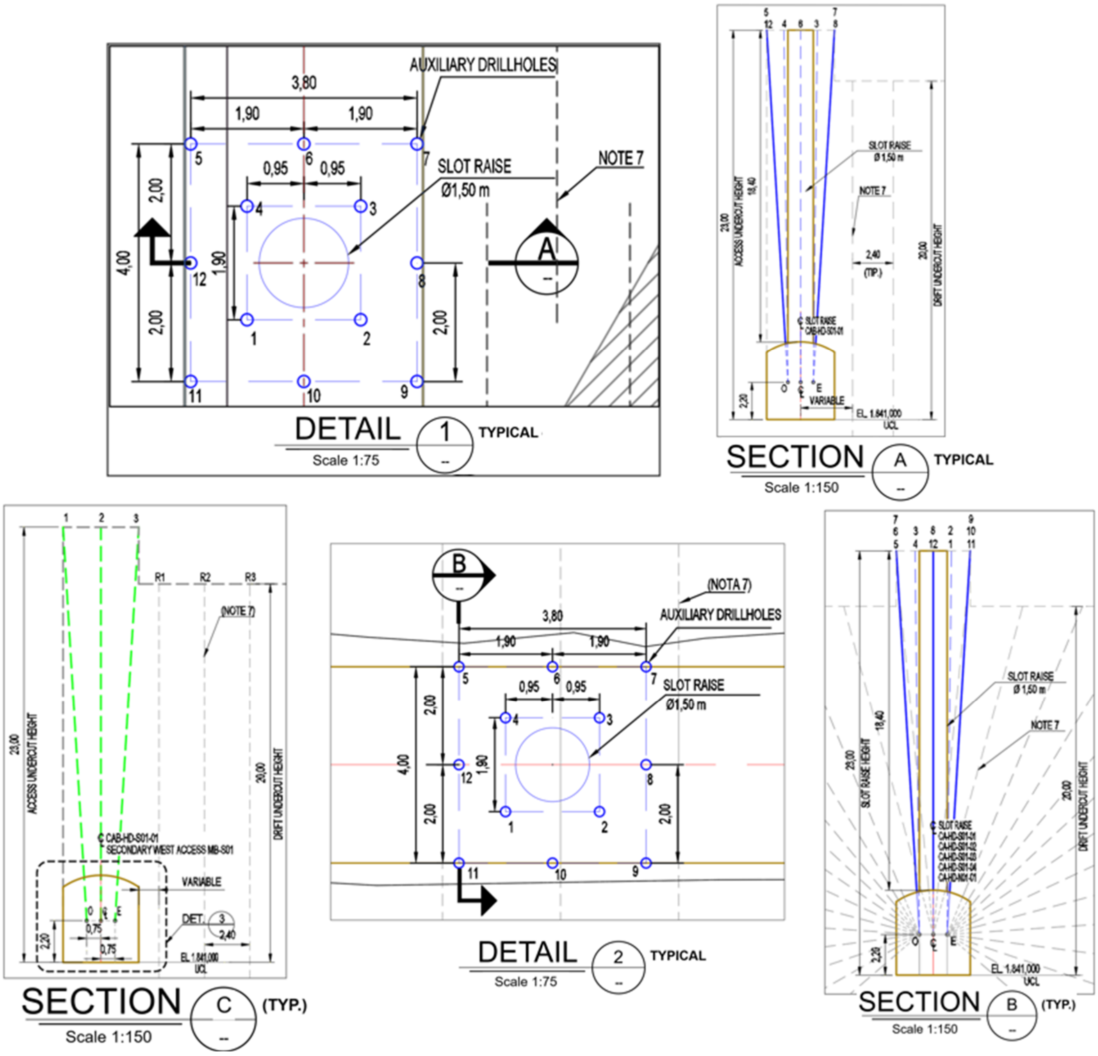


Figure 2 Drill and blast slot design in Central Macroblock – Sections views and patterns.

In the Central Macroblocks, a unidirectional opening strategy was followed. The slot was opened along Access Drift 01 (see Figure 3), opening the undercut drift as the slot passed through the intersection. However, the progress of the slot was not as expected. This strategy did not consider how to address the intersections and opening of the undercut drifts presenting problems of volume due to availability of free face, therefore, deficient blasting occurred that affected production plans. Since the strategy was unidirectional, it was not flexible in the case of unexpected events, and resources and time had to be invested in repairing the slot and undercut front to restart blasting. The main disadvantages of this strategy were: a lower rate of undercut area incorporation, low quality blasting and slower mucking.

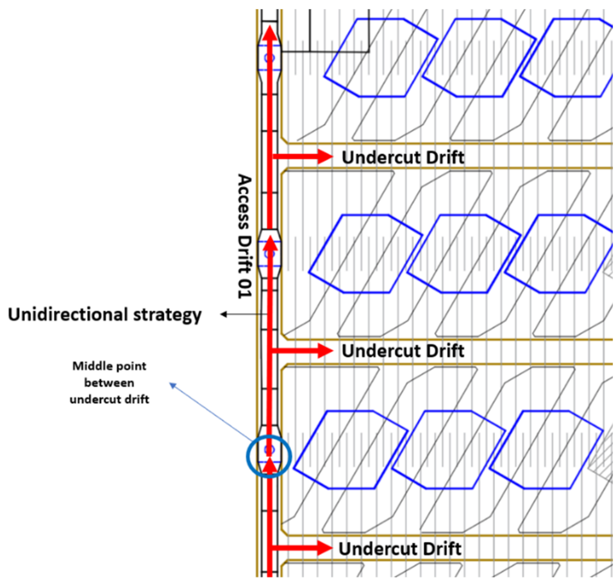


Figure 3 Unidirectional strategy for Slot blasting (UCL plan view).

As an example, during the undercut beginning in the Central Macroblocks during opening the undercut drifts, there was a risk of difference of time between the blasting of the slot intersection (XC Slot) (see Figure 4 – A) and the first blasting of the undercut drift (see Figure 4 – B), conditioning the incorporation of undercut area. All this due to the problems of free face and low flexibility that this unidirectional strategy presented.

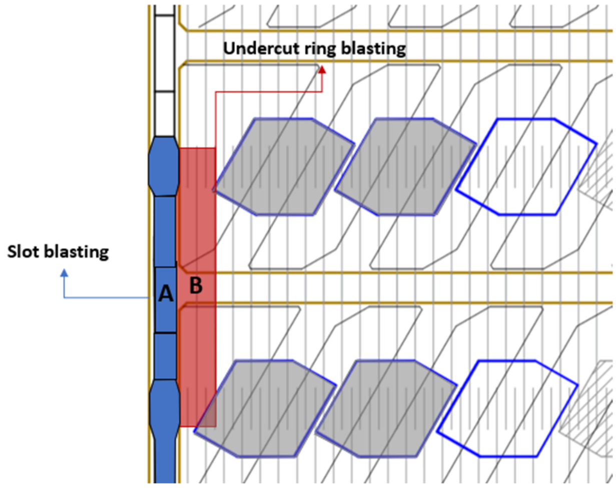


Figure 4 Time delay between XC Slot blasting (A) and undercut blasting (B) (UCL plan view).

2.3 Free face issue and Slot blasting

A unidirectional strategy does not allow the first undercut radial blast to be properly initiated due to the absence of a free face, confinement of blasted material or loss of drillholes.

The following problems can be expected:

- Lack of reception volume
- Massive blasting through access drift cannot be performed
- Undercut radial rings may be damaged on the XC Slot
- Radial rings confined
- Long distance from slot drift to crusher
- First drawbell position far away from XC Slot drift

To carry out the blasting of the first radial ring on an undercut drift, it is required that all the XC Slot blasting be performed (Slot blast N°1 to N°5 in Figures 5 to 7), in addition to the drawbell openings under the radial ring if is required.

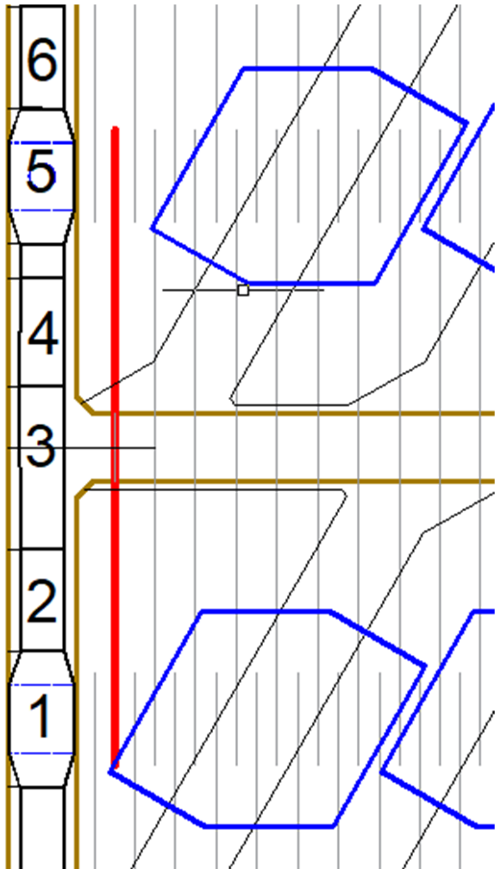


Figure 5 XC Slot blasting (N°1 to N°5) required prior undercut ring blasting (Plan view).

Blasts N° 1 and N° 2 and their respective mucking can be carried out without difficulties, but when planning and evaluating blast N° 3, this will cause the downholes of the first two radial rings to be obstructed with blasted ore. So, if necessary (when there is a drawbell under them), they must be blasted together with the intersection.

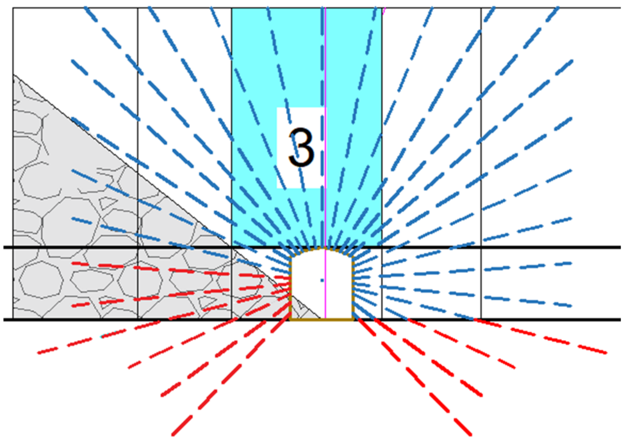


Figure 6 Radial ring and blast N° 3 of XC Slot (Section view).

Nor can the half of the radial ring that has a free face be blasted, because this will encounter blasted material and would also cover the half that does not have a free face yet (where Xc Slot N°5 and N°6 has not yet been blasted). Slot blast cannot be carried out in a larger volume (volumes of N°3 + N°4 or N°3 + N°4 + N°5) because there is not enough free face and it must be done in smaller phases. A blasting in the XC Slot has to be done before being able to blast the first radial ring in the undercut drift causes the wall drillholes to be obstructed due to the flow of the blasted material, preventing a clean first radial blast from being carried out having many times holes have to be drilled from the surrounding drift, in order to replace the holes that are blocked.

Even so, even if is possible to recover all the drillholes from the first radial ring (something almost impossible), the free face is full of blasted ore; which forces confined blasting and one ring at a time, reducing the quality of the blasting and the rate of area incorporation. When trying to take out mucking along the same drift street, the brow began to be damaged with the consequent loss of drillholes.

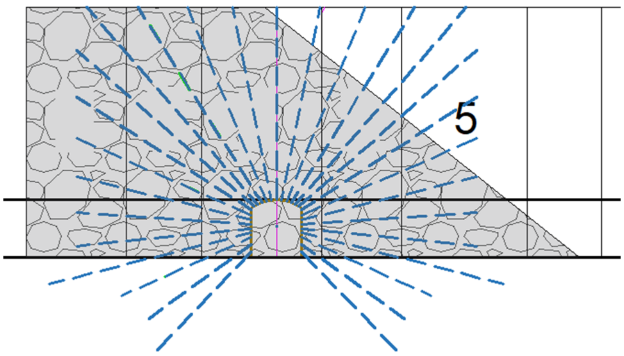


Figure 7 Radial ring confined with blasted ore in XC Slot (section view).

On the one hand, the lack of free face or sufficient volume after blast ore extraction did not allow larger blasts to be carried out to incorporate area, which resulted in a slower mucking, because great distances had to be travelled by UCL to an orepass that would connect to the Extraction Level, generating more time for incorporating drifts and undercut area; therefore, more time to reach ramp-up. Furthermore, if the first radial ring that has a drawbell under it is far from the XC Slot drift (see Figure 8), it forces the mucking extraction of the previous radial rings to be done by UCL, involving a much longer time than if the first radial ring connected to the drawbells below them and could extract ore by the Extraction Level, with LHD of greater capacity, with paved road in good condition and direct to an orepass or crusher.

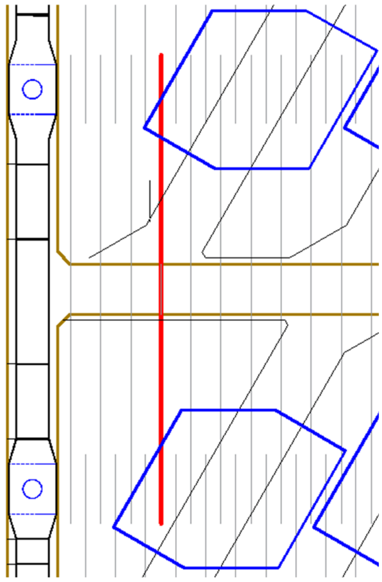


Figure 8 Radial ring over drawbell (red line) far away from XC Slot drift.

So, in the area of intersections (see Figure 9) blasting had to be carried out to open the undercut drifts and leave the front ready for the next undercut blast. However, this was not always possible given the low volume of reception, so in general the slot area in the intersections was blasted and the downholes of the first two radial rings were blasted in advanced, where for the north side they were burned only those who had direction towards the drawbells to protect the wall of the access drift and for the south side some semi-horizontal drillholes which were fired against blasted ore (see Figure 10), therefore, they were burned confined. The remaining drillholes were burned in the next blast since the slot in that area of the drift was not made (given the unidirectional strategy) and damage to the drift walls was avoided. However, during the extraction of mucking through the undercut drift, many times some of these drillholes were lost together with the brow.

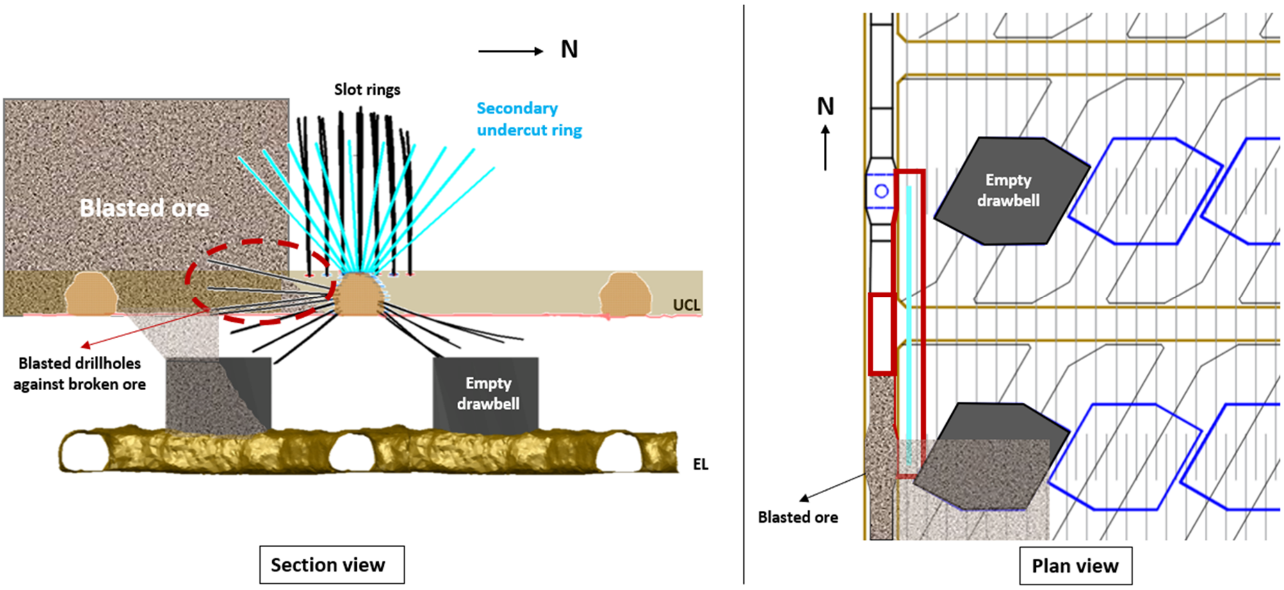


Figure 9 Blast design views for intersection XC Slot.

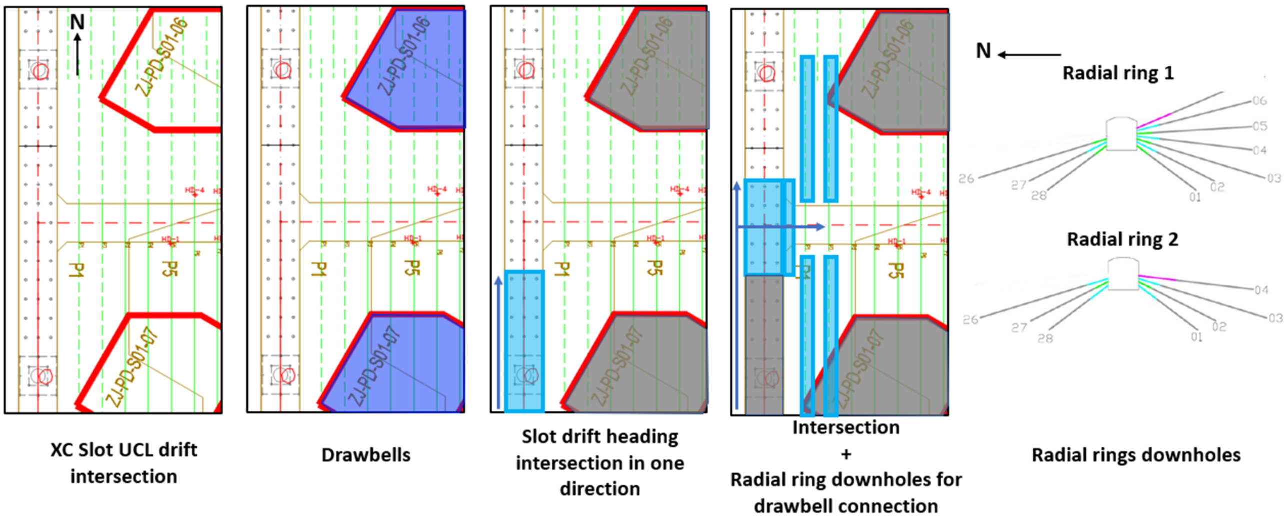


Figure 10 Blast sequence in intersection XC Slot.

2.4 Explosives charging

The charging explosives at the Chuquicamata Underground Mine in all production blasting including slot is performed under the following combination:

UBEX-ONE®: The system consists of a mechanized equipment (see Figure 11) that uses pumpable gasified emulsion (Duoblast-V®, Enaex. See Table 1) as a blasting agent. The sensitization is done in-situ where the condition of the explosive agent is obtained.

Table 1 Technical characteristics of gassed pumpable emulsion Duoblast-V®

Parameter	Value
Density (g/cc)	1.15 ± 5%
Velocity of detonation (m/s)	4,000 - 5,000
Detonation pressure (Kbar)	24
Energy (KJ/Kg)	2,736
Volume of gases (L/Kg)	1,087
Critical diameter (inch)	1 1/2
Resistance to water	Good

Figure 11 Ubex-One® Truck.

X-booster Up 250: Explosive charges with a High Power Pentolite ballistic tip, specially designed to be used in upholes in underground mining, in undercut areas and drawbells. This booster facilitates the priming operation and its placement can be done with the same emulsion charging hose.

Davey Tronic® UG electronic detonator: Designed specifically for the needs of demanding underground mining operations, the DaveyTronic® UG detonator includes the following features:

- Dynamic pressure resistance due to its durable copper coating and PCB protective resin.
- Resistance to electromagnetic pulse due to the intelligent design of its electronic module.

3 NEW STRATEGY

Based on the experience of incorporating the first Macroblock in Chuquicamata Underground Mine (see Figure 12 and Figure 13), a new incorporation strategy is defined, based on the position of XC Slot, location of raises for free face and evaluation of operational designs, as shown in Figure 14. The main objectives are to improve the volume availability and better address the blasting at the intersection of the XC Slot with the undercut drifts considering bidirectionality in the creation of slot raises through the access drift.

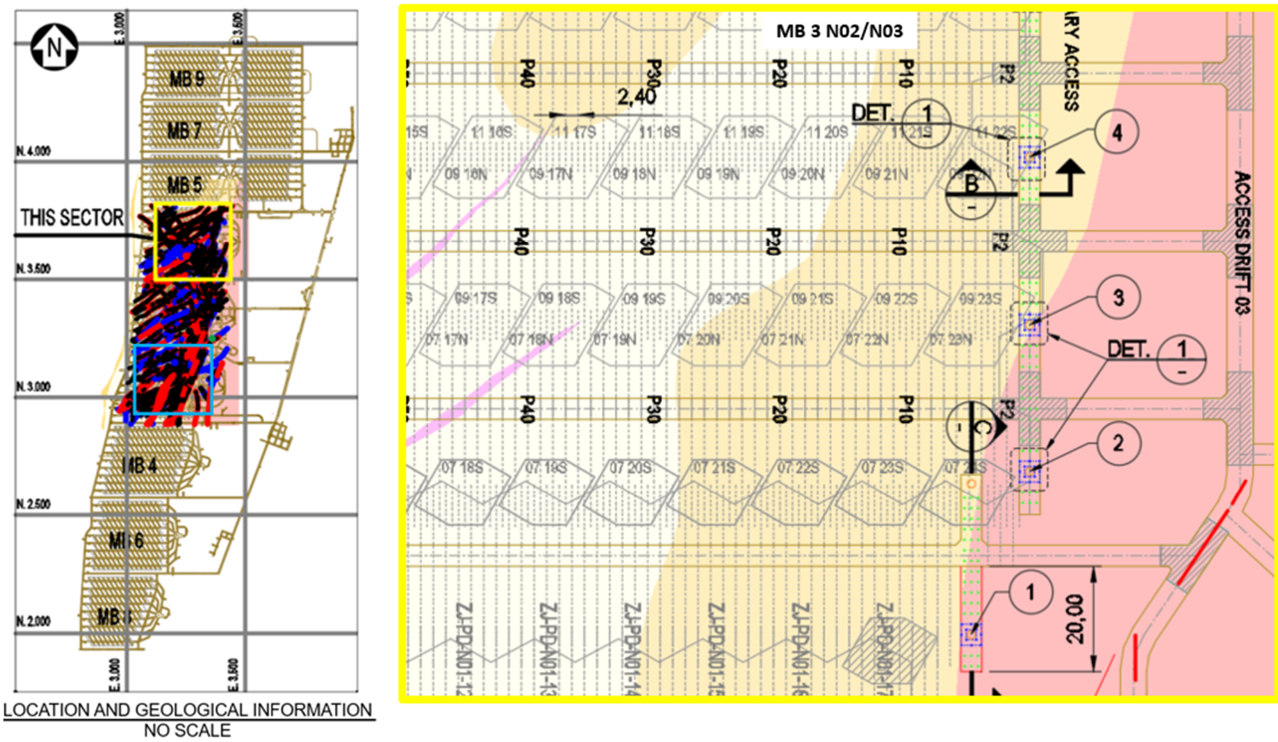


Figure 12 Drill and blast slot design in MB South and MB North - Plan view.

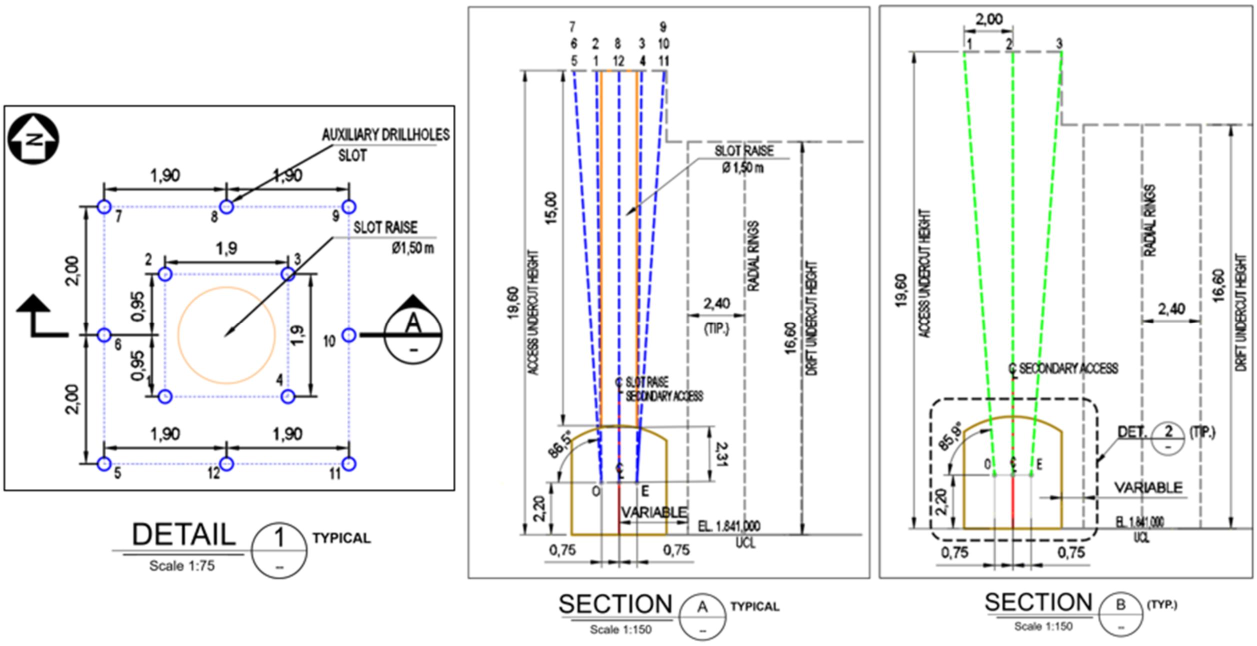


Figure 13 Drill and blast slot design in MB South and MB North – Section designs and patterns.

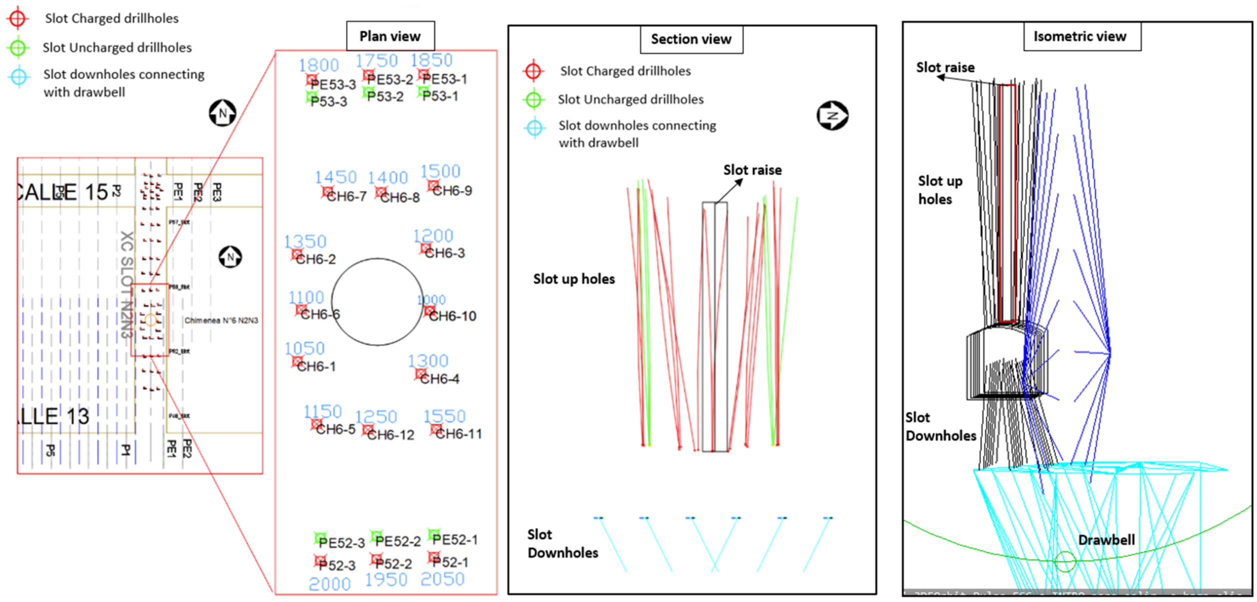


Figure 14 Blast design views for slot raise and intersection XC Slot.

3.1 XC Slot intersection

This new strategy proposes using the slot raises between undercut drifts and advancing in parallel, allowing tasks like measuring and preparing drillholes, scanning, mucking, charging, etc. to be carried out simultaneously. Progress is made in both directions in the XC Slot drift (see Figure 15), extracting the first blasted ore by the UCL and once the undercut height has been validated by means of a 3D scanner, the drawbells are opened under the XC Slot, connecting the undercut level to extraction level through them, due to they are strategically located under or just to the side of the XC Slot and are designed with raises reaching the undercut level floor, with slightly longer drillholes towards the XC Slot which, together with downholes from the floor of the slot drift, ensure the connection between levels. This allows the remaining blasted material to be evacuated completely to the drawpoint at the Extraction Level and extracted directly to the orepass or crusher, with LHD of greater capacity and with paved road designed for correct extraction. Compared to the strategy followed in the Central Macroblocks, the difference lies in the location of the open drawbells and the bidirectionality of the slot. Subsequently, another blast is performed on each side to finally blast the intersection between drifts. In addition, it is possible to advance with downholes and semi-horizontal holes on both sides of the undercut drift, or blast the intersection with radial rings if required. With this strategy, very good free faces are generated for the blasting of the first radial rings and it also allows it to start cleanly and with quality.

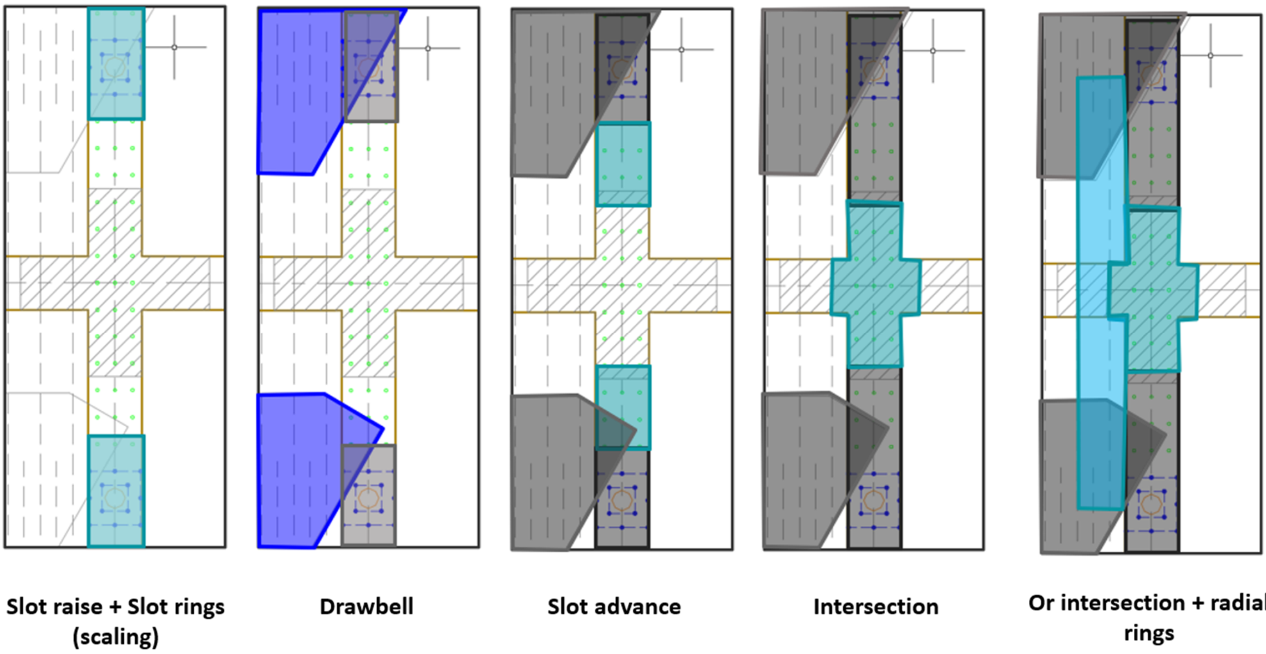


Figure 15 Blast sequence in XC Slot intersection with undercut drift.

As Figure 16 and Figure 17 show, it is possible to connect the blasted XC Slot to the Extraction Level through the drawbell and remove all the ore blasted through the drawpoints towards an orepass or crusher, allowing to drastically reduce the mucking times, in addition to being able to work in parallel in different combinations Slot – Drawbell, as they are multidirectional fronts.

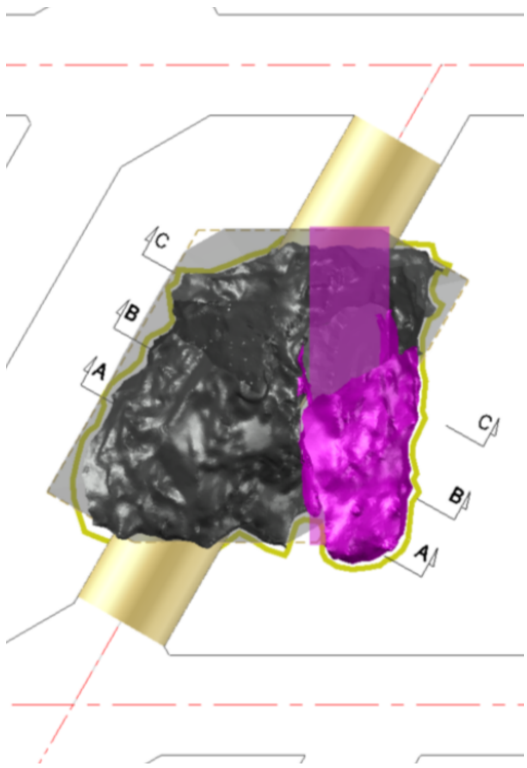


Figure 16 Plan view of a drawbell connected to Xc Slot drift.

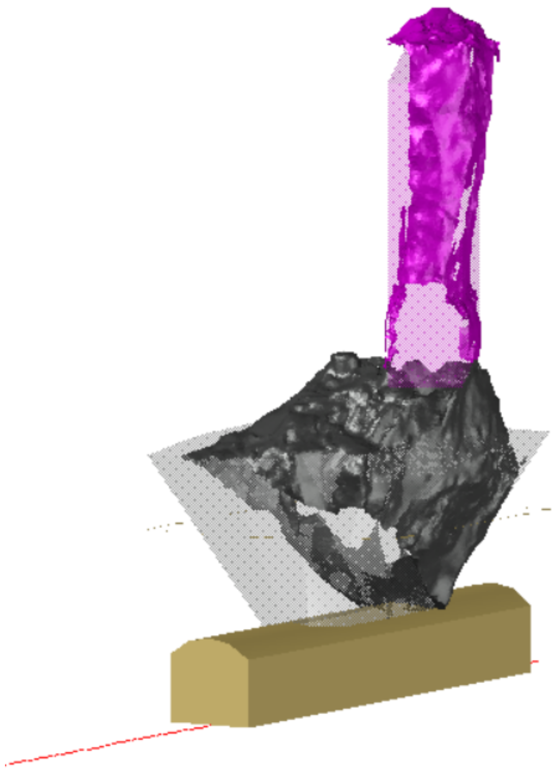


Figure 17 Section view of a drawbell connected to Xc Slot drift.

Regarding the design of blasting at the intersections, the difficulty lies in the double burden at the end of the blast, so a hole-by-hole strategy is defined by approaching the center of the intersection and right there it turns into a rhombus-type blasting (see Figure 18), where the drillholes detonate at the same time to avoid the problem of multi burden. If there is a problem with the blasting at the end that generates some remnant (which has not yet happened), this will remain on the undercut drift, so it will not be able to generate point loads.

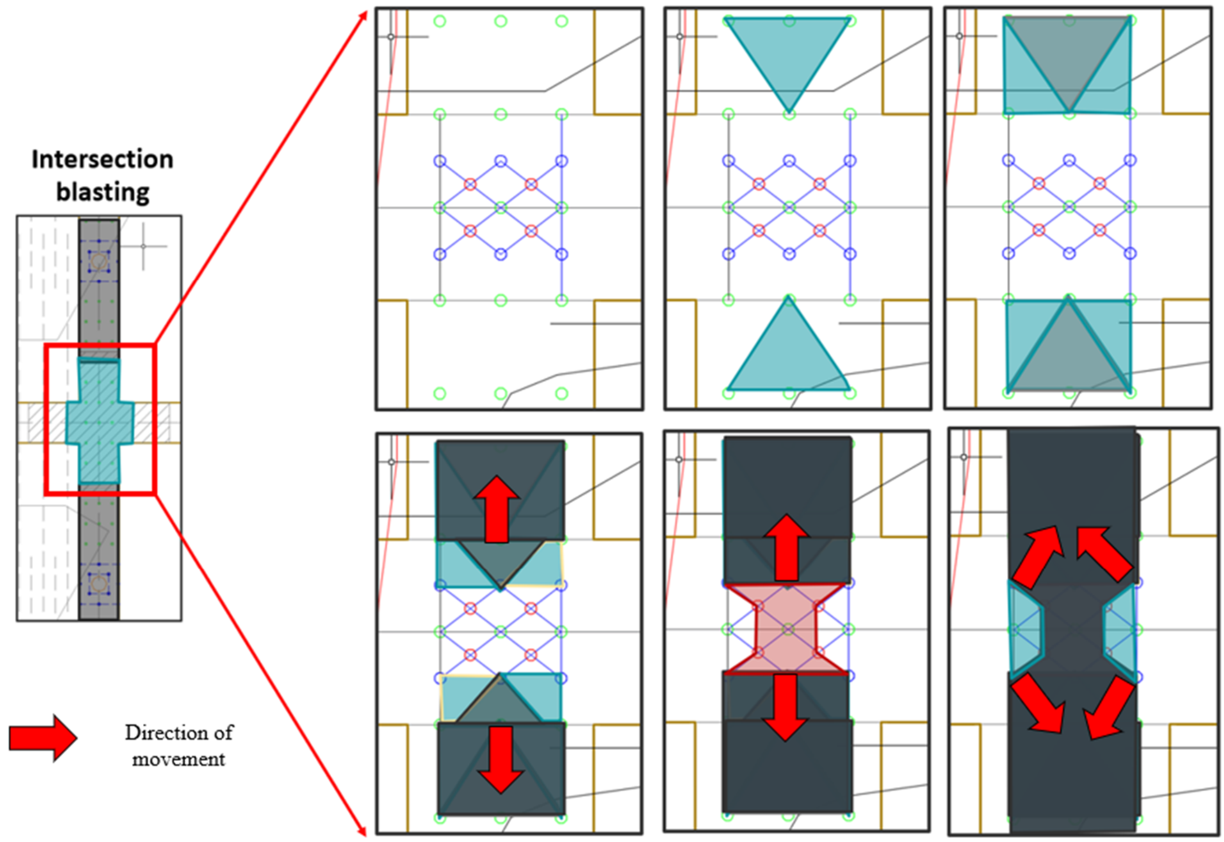


Figure 18 Blast strategy in intersections.

4 EVALUATION OF NEW STRATEGY METHODOLOGY

The methodology to evaluate the results can be summarized in the chart of Figure 19.

It is important to highlight that every stage was monitored in different aspect. Since the design, preblast measurement, Quality Assurance/ Quality Control (QaQc) drill and blast and post blasting analysis including the base line of Central Macroblocks.

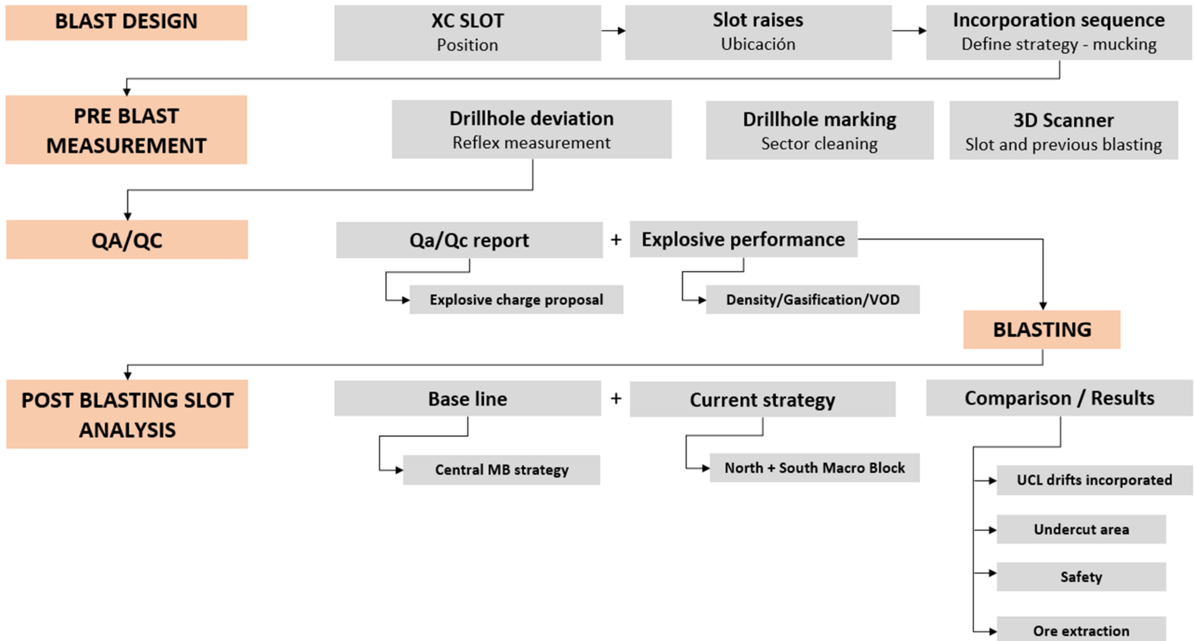


Figure 19 Evaluation results slot blasting methodology.

5 NEW STRATEGY EXECUTION

Since the beginning of its operation, Chuquicamata Underground has been developing a complete QaQc process for blasting in conjunction with the Technical Area of Enaex.This process seeks to have control and registration of each process that involves blasting. The D&B cycle is summarized in the diagram in Figure 20. The new slot blasting strategy is subjected to Qa/Qc control for each blast carried out in the mine.

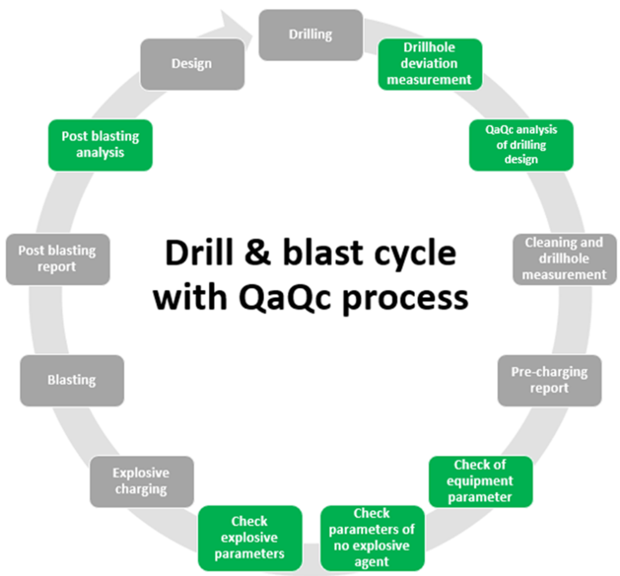


Figure 20 D&B cycle with QaQc process.

5.1 Pre-blasting control

The control prior to drilling and charging explosives begins with cleaning the sector (see Figure 21), marking the upholes rings and the position of the collars across the slot drift. This stage becomes important when ensuring a good positioning for production drilling and ensuring that boreholes are within the acceptable parameters with respect to the theoretical design.

Figure 21 Marking and cleaning drillholes.

Then, drilling control is performed by measuring borehole deviation with Reflex Blastrac equipment, a task carried out by the Enaex Technical Assistance Department and the correspond analysis and QaQc reporting. The analyzes involve drilling compliance in terms of spacing, burden, length and inclination. Then, the respective energy distribution analysis is done with the purpose of looking for possible areas with low energy concentration due to the deviation, as shown in Figure 22 and Figure 23. If required, re-drilling of blastholes is done in the areas that require increasing energy concentration or height. The explosive energy distribution is a crucial part on the drill & blast QaQc process as if the analysis and recommendations are not performed, the blasting is not authorized.

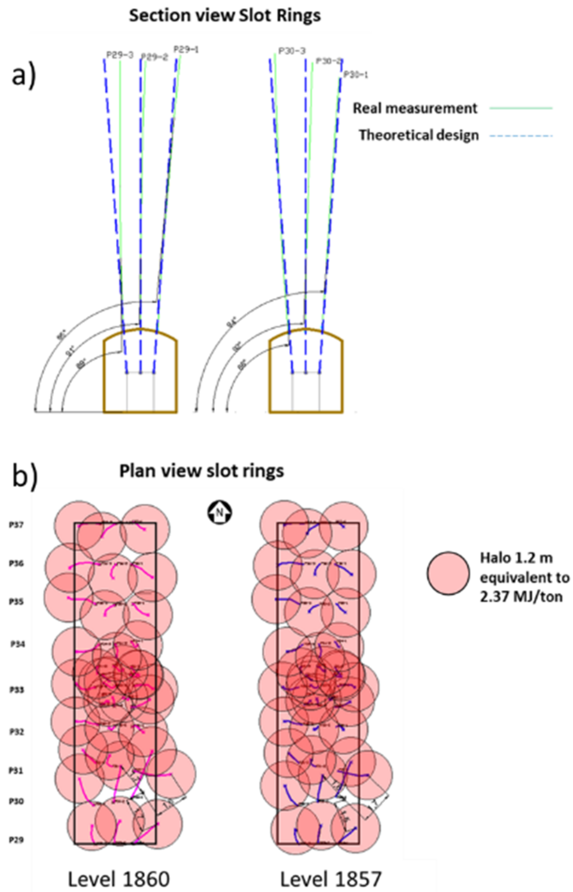


Figure 22 QaQc control of drilling.

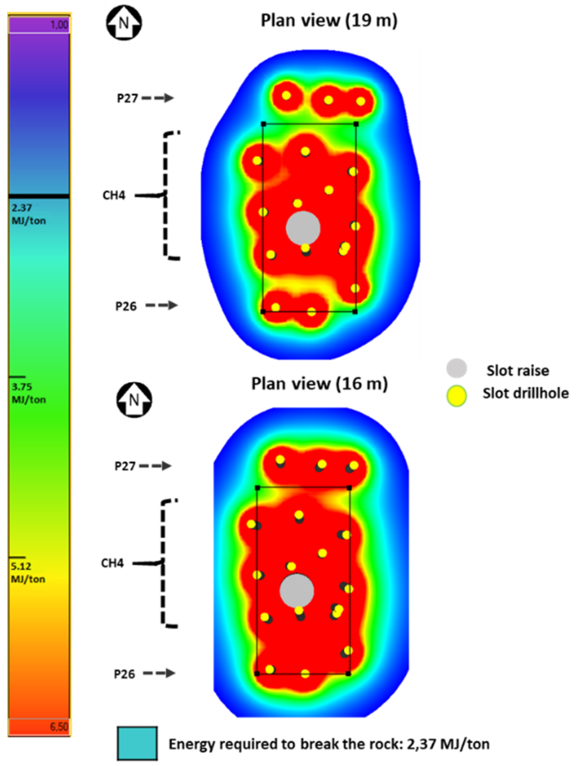


Figure 23 Explosive energy distribution analysis.

5.2 Post-blasting control

5.2.1 3D Scanning

Blasted ore from each slot blast is extracted and at the moment a space in the slot front is generated the results are scanned. The above is a fundamental control that confirms that the entire free face of the available slot is maintained. Given the nature of the new strategy used in Chuquicamata Underground Mine, the mucking is carried out from the drawpoints in the extraction level, being able to leave volume available, both for scanning and for free face. Figure 24 shows the scanner prior to blasting at the intersection between Xc Slot and undercut drift where the available volume on both sides of the intersection can be seen. This greater volume of free face available gives the opportunity to perform the first undercut blast with complete radial rings and not just downholes as in the strategy followed in the central macroblocks.

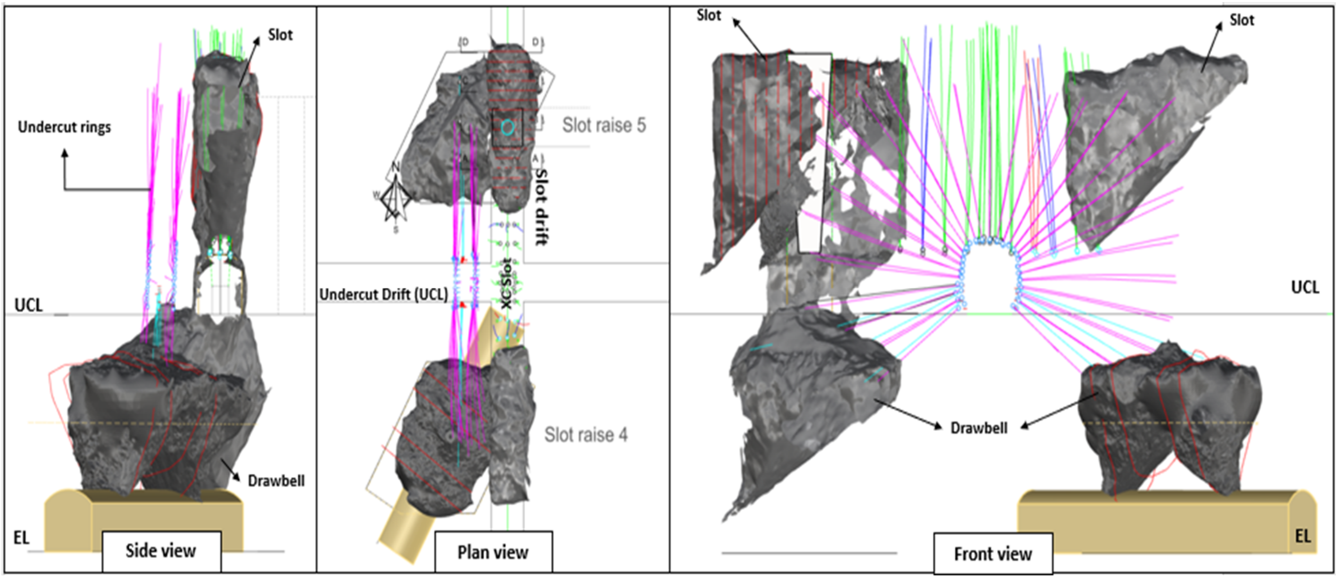


Figure 24 3D scanner post slot blasting prior XC Slot.

5.2.2 Fragmentation

Like undercut and drawbell blasting, the fragmentation results of the post-blasting mineral are measured. This is done through photogrammetry and analysis with the Wipfrag software (see Figure 25) using images of post-blasting pile fragmentation, as shown in Figure 26. The analysis is made over the surface of the blasting fragmentation pile using 1-meter reference. The above allows not only to maintain an idea of how the blasting was carried out, improve material handling and optimize the crushing operation but as well to analyze over burden/spacing due to hole deviation as higher fragmentation may be found on the pile. In general, the slot blasting performed showed an average P(80) value of 300 mm indicating a fine fragmentation easy to handle.

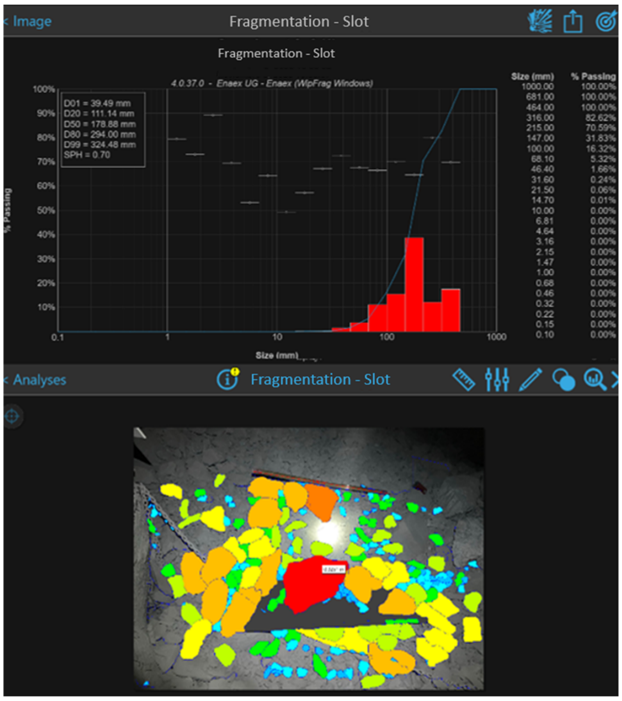
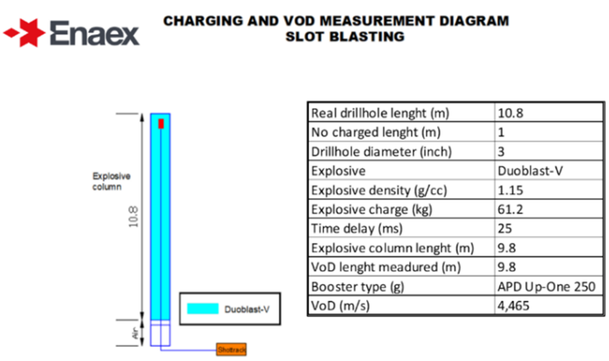


Figure 25 Fragmentation analysis by Wipfrag.

Figure 26 Post-blasting fragmentation pile.

5.2.3 Velocity of detonation (VoD)

Within the quality control of bulk explosives manufactured in-situ, it is relevant to maintain control over the VoD. In the case of Duoblast-V® explosive, it must maintain a VoD between 4,000-5,000 m/s. To do this, the measurement is conducted using ShotTrack VOD 305 equipment, installing the coaxial cable in the prime of the first shot of the initiation sequence. The charging and measurement scheme are shown in Figure 27. A VoD measurement example is shown in Figure 28, where the VoD obtained for the explosive column detonation (~4,800 m/s) is in the range indicated above.



Real drillhole lenght (m)	10.8
No charged lenght (m)	1
Drillhole diameter (inch)	3
Explosive	Duoblast-V
Explosive density (g/cc)	1.15
Explosive charge (kg)	61.2
Time delay (ms)	25
Explosive column lenght (m)	9.8
VoD lenght meadured (m)	9.8
Booster type (g)	APD Up-One 250
VoD (m/s)	4,465

Figure 27 VoD measurement diagram.

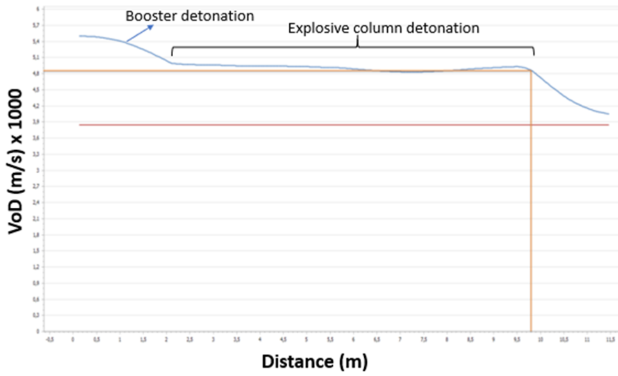


Figure 28 VoD measurement example.

The VoD obtained during all the slot blasting (57 events) with this new strategy indicated an average of 4,420 m/s indicating that the explosive had a good performance due to proper control of the in-situ manufacture. This result matched with the good fragmentation obtained.

5.2.4 Vibration

Vibration monitoring is carried out with an Instantel equipment and triaxial geophone joint to the rock mass or geophone embedded with grout inside a borehole with a triaxial arrangement. The vibrational records of the explosive charges (see Figure 29) allow the engineers to know the performance of the blasting in terms of the number of detonated charges and confirm their detonation sequencing. This is important to be sure that every charge in every drillhole detonated and not expect misfires after blasting. The detonation sequence for the slot upholes surrounding the slot raise are crucial as it opens the free face for the rest of the slot blasting. In order to monitor the blasting, the geophone was installed 50 meters from the blasting. The monitoring was done for every basing. The figure shown below is the vibration monitoring for slot raise blasting sector with its detonation sequence. Monitoring allows confirming the detonation of each explosive charge.

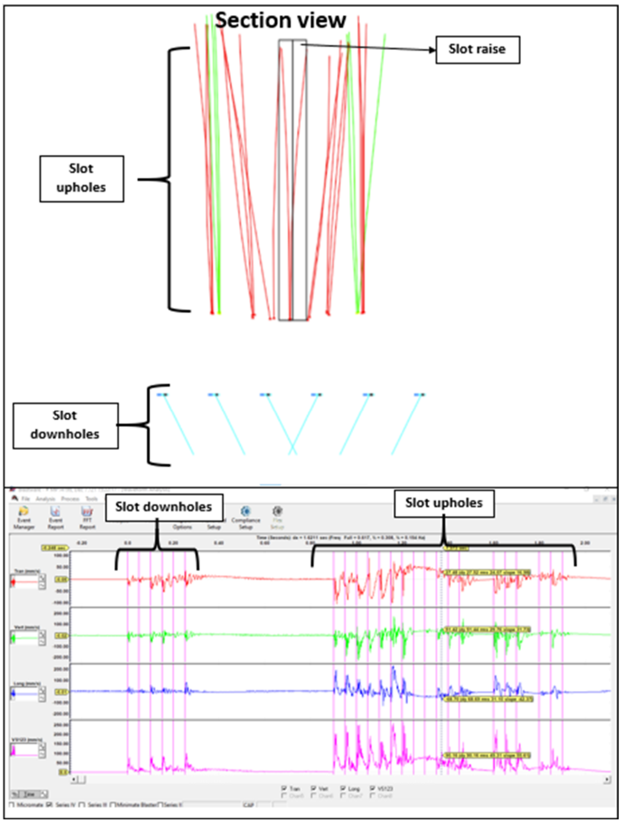


Figure 29 Vibration monitoring.

5.3 Mucking

Locating the drawbells under or immediately to one side of the Xc Slot drift, and performing a D&B design that enables the connection between both undercut and extraction level, allow most of the blasted ore from the Xc Slot to be extracted through the drawpoints, using the paved road, LHD of greater capacity and much shorter distances. The above reduces the mucking time between four and five times, compared to the experience of the Central MBs where the lower LHD capacity, which allow maneuvering in closed curves, had to travel greater distances on unpaved drifts until finding a shaft to empty, also requiring a second LHD in the extraction level to maintain capacity in the orepass and ensure continuity.

The unidirectionality of the advance of Xc Slot in the Central Macroblocks forced each unitary operation to be accomplished, one after another. Thus, for example, the mucking had to be completed 100% to scan and the LHD was waiting for the scanner, the measurement and preparation of boreholes, the charging and blasting before the next muck extraction; while with the new strategy the LHD always had a material to extract, since it had more than one job to do in parallel (extract ore from the drawbell and the Xc Slot in more than one slot front at a time).

The multi-directionality and the correct position of the Xc Slot-Drawbell allow to optimize strategies in free face quality and mucking times, drastically reducing the Ramp-Up time of undercut area incorporation and production plans.

5.4 Safety

The proposed design and strategy are in line with the values of Codelco and Enaex and in addition to being a very good operational strategy, it does not expose people to carrying out risky tasks, The explosive charging with Enaex is always mechanized, charging is always by the opposite side to the side where the blasted ore is extracted and remains with a “window” or space. Therefore, the new strategy is much safer.

6 CONCLUSIONS

It is important to create slot raises with the objective of initiating undercutting or accelerating the undercut area incorporation process in Block/Panel Caving operations. As there is no enough documented data regarding how open slot for this caving method, the proposed methodology is relevant from the blasting point of view, which may present operational complexities.

It is possible to see that, by changing the undercut strategy from what was followed in the Central Macroblocks. The new strategy proposed and used in the North and South Macroblocks had important changes in the improvement of the process. That is, in the availability of free face for the blasting of intersections, increase in the rate of mucking, greater incorporation of drifts over time, greater incorporation of undercut area.

The new strategy presented in this document improved every aspect of the drill and blast cycle. Like in safety (it is never charged on the same side of mineral extraction), in mucking times when the drawbell is strategically under or immediately next to the Xc Slot. All of these aspects decrease drastically. In addition, there is the possibility of working on different fronts in parallel improving productivity and decreasing ramp-up time. The QaQc methodology followed for assuring the success of the slot blasting permitted to control the process since the drilling until the post-blasting. Finally, being able to perform a clean initial radial ring undercut blast, without losing drillholes. For all the above, already proven by undercutting three Macroblocks, the new strategy is validated.

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