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Reactivating mud-affected drawpoints at El Teniente mine

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Abstract

Mud rush is one of the most significant hazards at El Teniente mine, characterised by the sudden inflow of large amounts of fine-grained material mixed with water, typically originating from either the surface or abandoned upper levels. Tactical risk management plans include draw control and strategies, continuous ore sampling, machine learning–based mud rush risk assessment, and closure of high-risk drawpoints. These plans have recently been improved through the use of semi-automated extraction equipment to meet higher safety standards while maintaining target production rates. In this context, managing the reopening of closed drawpoints affected by mud rush risk is considered a novel approach in cave mining, especially at El Teniente mine. Understanding how semi-automated technology, combined with appropriate operational strategies, can enable the reactivation of natural flow in mud-affected drawpoints is essential for developing guidelines on draw control and reopening practices. Ultimately, the goal herein is to safely recover lost ore reserves that were previously abandoned due to mud rush risk.

This article provides a structured operational strategy for reactivating closed mud-affected drawpoints at Dacita mine, which is one of the operations at El Teniente mine. The strategy first involves characterising drawpoints and assessing the automation status in the production level to establish the most suitable reopening sequence for restoring gravity flow. Subsequently, a prioritisation process is carried out based on production variables, geological parameters, operational risks, exclusion zones, as well as secondary breakage and drill-and-blast plans. Ultimately, this strategy provides cave mines with a reliable alternative to safely recover ore reserves, and makes it possible to potentially increase the production rates without requiring cave growth. The lessons learned in Dacita mine will serve as key knowledge for future cave mining projects at El Teniente mine.

Keywords: *caving methods, mud rush, reactivating gravity flow, caving operations*

1 Introduction

Cave mining, including block and panel caving, has become one of the preferred underground methods for massive mineralisation in hard rock environments at depth since it is a highly productive, low-cost mass mining method (Heslop 2000; Brown 2003; Flores-Gonzalez 2019). In block/panel caving, a portion of the orebody is progressively collapsed by undercutting from the undercut level, and the sustained draw from drawpoints at the extraction level promotes the cave propagation.

As extraction continues, ore columns naturally cave through the orebody until the cave back breaks through to the surface or into existing caves. The breakthrough of a cave subsequently leads to a phenomenon known as subsidence, which is a large-scale deformation on surface. Subsidence is, therefore, an inherent result of mass caving methods.

Nowadays, most of the underground caving operations are naturally affected by the mud rush risk as the subsidence zone has the potential to accumulate water, and thus, generates water inflows toward the broken ore column (see Figure 1a). Mud rush has been widely recognised as one of the major risks in several caving environments, such as intermediate ore zone (IOZ) mine (Hubert et al. 2000), deep ore zone (DOZ) mine

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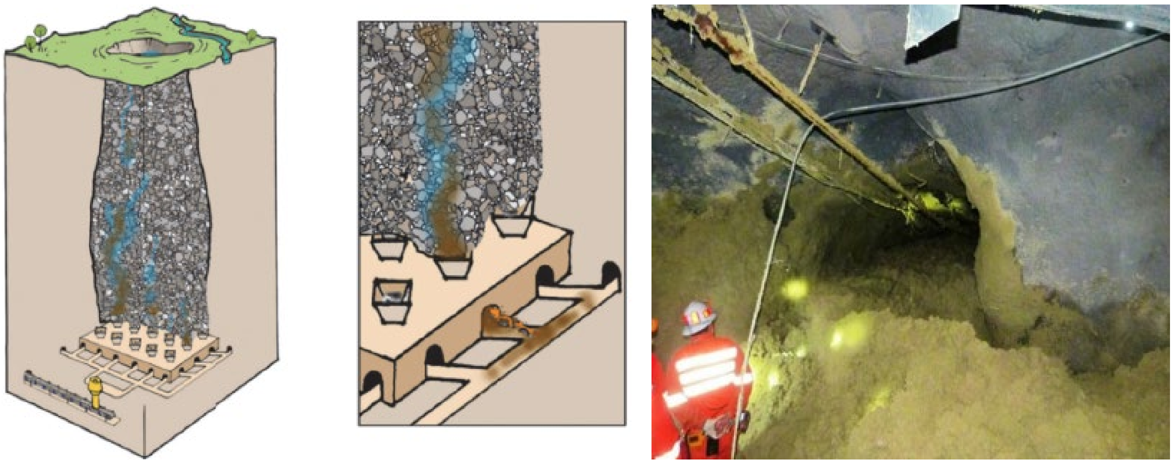
(Syaifullah et al. 2006; Samosir et al. 2008; Widijanto et al. 2012), El Teniente mine (Becerra 2011; Ferrada 2011; Garcés et al. 2016; Castro et al. 2018) and Kimberley underground mines (Holder et al. 2013). Mud rush is a sudden inflow of material composed of unsorted fine rocks and groundwater that flows by gravity and has the ability to discharge at a drawpoint or other mining opening (e.g. ore passes, chutes, chimneys, among others). Ultimately, mud rush may cause significant safety issues and considerable economic losses. Figure 1b depicts the occurrence of a mud rush at El Teniente mine.



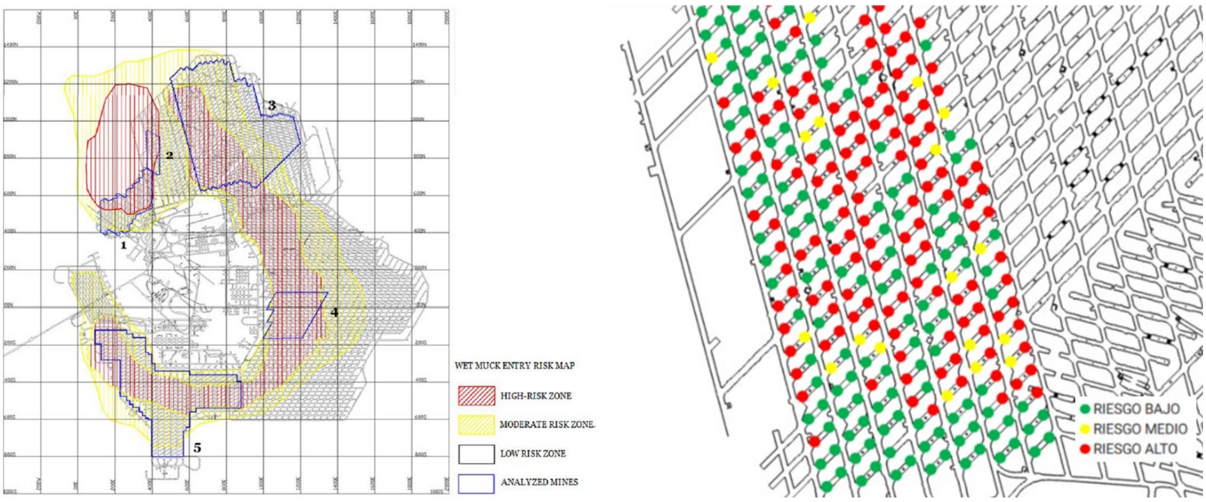
(a) (b)

Figure 1 (a) Schematic representation of water inflow into the broken ore columns and the occurrence of a mudrush (Flores-Gonzalez 2019); (b) Occurrence of a mud rush at a drawpoint in the extraction level during mine operation in El Teniente mine (Codelco 2016)

Operational experience from large cave mines has highlighted the relationship between subsidence, water accumulation from surface, draw rates and mud rush occurrence. At Palabora mine, the interaction between the multiple caves generated uncontrolled, free flow of fine material. By 2007, a total of 152 wet inrushes had been recorded. Due to the inrush risk, drawpoints classified as high-risk were sealed off, and draw strategies to promote water drainage were therefore not applied (Paetzold et al. 2020). Similarly, at DOZ in Grasberg mine, wet muck events are caused by the interaction of significant water accumulation on surface (high rainfall all year), several overlying cave mines and the presence of fine mud-forming materials, and later spread in the surrounding area due to lateral migration and rilling of fine ore (Widijanto et al. 2012). Some key lessons learned are the importance of continuous and even drawing to reduce water content within ore columns and the implementation of tele-remote loaders to improve the equipment for mud material handling, reducing personnel exposure while maintaining the continuous drainage of groundwater at drawpoints.

The experience from El Teniente mine is related to multiple cave mines, such as Pipa Norte, Reservas Norte, Dacita, Diablo Regimiento and Esmeralda mines (Garcés et al. 2016; Castro et al. 2018). Most of these operations experienced cave breakthrough to upper abandoned mines, where mud rush is intrinsically related to the interaction between a mature cave subsidence, caved fine material and draw strategies. In the past, when mud rush risk assessments relied solely on operational expertise and on site conditions, drawpoints experiencing high water content and high presences of fines were closed, ceasing extraction immediately and abandoning ore reserves from production plans. Consequently, to deal with mud rush risk, El Teniente mine adopted draw criteria depending on a deterministic mud rush risk map categorising 3 types of risk zones, based on the water content and the presence of mud-forming material (Castro et al. 2018). Additional details on the mud rush risk map are shown in Figure 2a. Due to mud rush risk being significant in recent years, El Teniente mine has continually enhanced the drawpoint classification systems, and currently, this control is based on a machine-learning mud rush risk map that considers groundwater content at drawpoints, distance to surface, uniformity of draw and rainfall data (Figure 2b). Thus, guidelines are provided for controlled draw strategies using autonomous load–haul–dump (LHD) operation to reduce personnel exposure.

Although El Teniente mine has significantly improved its mud rush risk control systems to support continuous mine production, technical and operational analysis of recovering abandoned ore reserves for increasing current mine production has only been addressed in recent years. In this regard, the use of semi-autonomous LHD units alongside a better understanding of mud rush phenomena at El Teniente mine provided opportunity to carry out multiple operational activities to reactivate the gravity ore flow at drawpoints abandoned due to mud-related risk conditions. This paper describes the experience learned at El Teniente mine during the reopening of such drawpoints, where several mine strategies had to be carefully designed, tested and validated to successfully restore the gravity flow in long-abandoned drawpoints. For this purpose, Dacita mine was considered the case study for initial trials on this matter. Details of mine strategies, operational implementation and key learnings from the reactivating program are provided.



(a) (b)

Figure 2 (a) Mud rush risk map used at El Teniente mine. The red zone (high risk zone) describes the area with low elevation (topographic gutter), less than 500 m, with intermittent flows from melting snow and rainfall. This area is characterised by the presence of historical wet muck flows. The yellow zone (intermediate risk zone) corresponds to the area within the topographic gutter with an elevation higher than 500 m, where wet muck inflows were registered. The remaining area classified as white zone (low risk zone) indicates an area with high elevation (greater than 600 m) located outside the topographic gutter's influence, where wet muck inflows were unregistered (González & Brzovic 2017); (b) Machine-learning mud rush risk map currently applied in El Teniente mine

2 Case study

2.1 Dacita mine overview

El Teniente mine is comprised of several cave mines located around a subvolcanic chimney known as the Braden Pipe. Dacita mine is situated on the northwestern side of the El Teniente complex, next to Reservas Norte mine, which is considered as an extension of this productive sector (see Figure 3). Early mining activities started in August 2011, and production started in November 2013 at a production rate of 17,000 t of ore per day. The mining method was a conventional panel caving with post-cut undercutting with hydraulic fracturing and an integrated mine design that allowed drawbells to be connected between Dacita and Reservas Norte mines.

Primary rock columns heights are roughly 180 m on average, ranging from 80 to 250 m. Lower-height columns are located beneath the Sur Andes Pipa and Pipa Norte mines, as seen in Figure 3. The cumulative effect of multiple large caves surrounding the Dacita mine generated an increased pre-mining stress condition, comparable to those observed in Reservas Norte mine, even in areas with lower column heights (Espinoza & Landeros 2014).

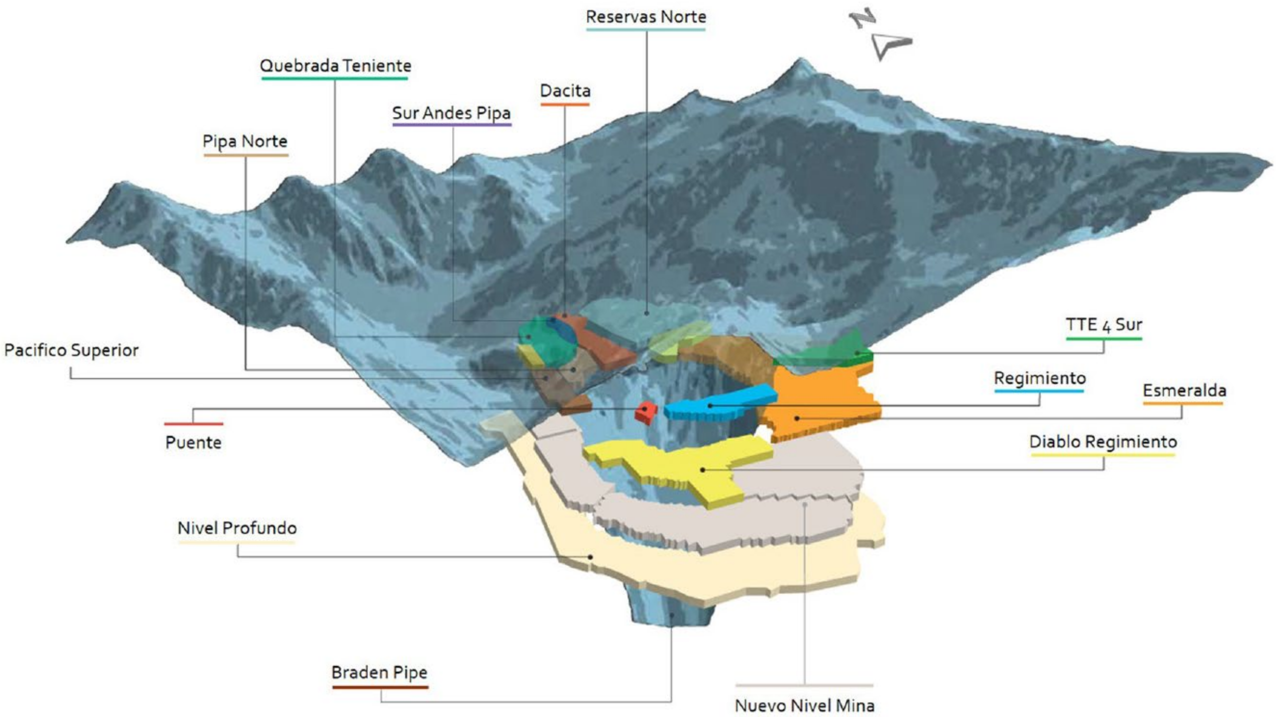


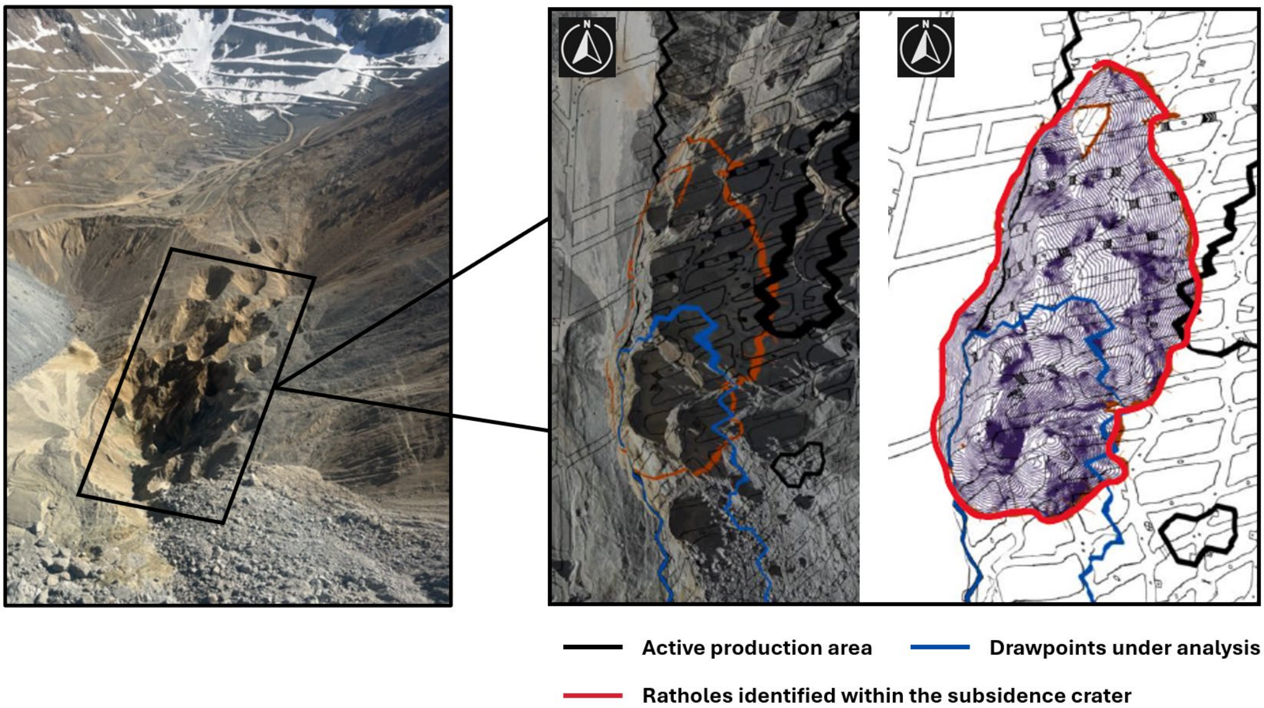
Figure 3 Isometric view of productive sectors at El Teniente mine indicating the location of the studied mine (Codelco 2016)

2.2 Surface conditions at the study area

Subsidence at El Teniente mine is a consequence of progressive cave breakthrough of multiple mines over decades of production. Fractured surface and topographic depressions play a key role in controlling the water infiltration as they modified natural patterns on surface, providing preferential catchment zones for water accumulation from rainfall and snowmelt. These pattern and permeability changes promote infiltration into cave columns; this is particularly relevant in cases where local craters or rat-holes allow the water to migrate rapidly from surface to drawpoints at the extraction level.

Experience from different operations at El Teniente mine demonstrates that mud inflows are initially associated with a vertical inflow mechanism from craters or rat-holes above cave mines, and then, a lateral migration mechanism occurs in the surrounding neighbouring drawpoints, increasing mud rush risk around the rat-holing (Garcés et al. 2016; Castro et al. 2018).

Figure 4 depicts a portion of the subsidence zone from a georeferenced image, which is located above Dacita mine. The appearance of several rat-holes to surface throughout operating have caused an increase in the Dacita crater in terms of area and depth; therefore, drawpoints affected by this topographic depression are of great importance in establishing draw strategies and ground control.



(a) (b)

Figure 4 (a) Georeferenced image of the El Teniente mine's cave subsidence; (b) Corresponding analysis for the case study

3 Method

Restoring the gravity ore flow in closed mud-affected drawpoints is one of the most challenging operational tasks in a mature cave mine such as El Teniente mine. These drawpoints commonly have high proportion of fine material, water accumulation within ore columns, and therefore, high degree of compaction inside the drawbell. The reactivation process under such conditions requires an integrated framework that simultaneously manages mud behaviour at drawpoints, automation and control systems, and operational execution under high uncertainty.

The proposed operational framework is based on the underlying premise that successful ore flow reactivation can only be achieved when ground control knowledge, controlled draw strategies, and automation for materials handling are combined not only for extracting purposes, but also for reducing the exposure of mine workers.

The framework is composed of the following 5 steps:

1. On site control and monitoring: refers to specific activities that help both minimise and better understand the occurrence of mud rushes, the evaluation of heights of draw, proportion of fines, water content and the location of potential rat-holes or craters on surface. As mentioned above, significant surface depressions serve as preferential water infiltration paths in mature cave operations, promoting steady, long-term saturation within the cave column without prior notice. An evaluation of the distance to surface is carried out for each drawpoint inside the autonomous-operated layout, including those considered for flow reactivation.
2. Extraction strategies and secondary breakage: has 2 main goals – developing an airgap inside the drawbell to promote stress redistribution (in particular, shear stress) and preventing the re-compaction of caved fine ore. This step is of great importance since the operational execution must minimise the occurrence of sudden mobilisation of saturated fine ore, which may compromise personnel safety and mine infrastructure. The step is considered complete once the airgap reaches

a volume at which the autonomous LHD unit cannot muck and secondary breaking activities cannot be carried out safely or effectively.

3. Drilling and blasting: provides designs adjusted to the conditions of each drawbell to be reactivated. The goal here is to destabilise the volumes of contact that provide support to the compacted ore column along drawbell walls. For that purpose, 3D georeferenced laser scanning is carried out through the extraction drive and inside the drawbell, allowing the as-built drilling design to be implemented on site. Blasting is conducted immediately after drilling to reduce possible loss of blastholes due to decompaction inside the drawbell.

4. Control and monitoring: aimed to promote gradual restoring of gravity flow rather than immediate tonnage for production purposes. Reactivation performance is evaluated through a defined set of operational key performance indicators (KPIs), described as follows:

   - Drawpoint reactivated: indicates when a drawpoint successfully achieves the reactivated ore flow state. For that purpose, the following 3 defined KPIs have to occur simultaneously:

     - Accumulated tonnage: a reactivated drawpoint must reach 3,200 t during the reactivation process.

     - Hang-up frequency: a reactivated drawpoint must reach a frequency >400 t/activity. This indicator is closely related to the secondary breaking performance.

     - Reactivated neighbourhood: at least 2 neighbouring drawpoints have to be reactivated in the surrounding area. This is key to ensuring the connection between the reactivation and the current flow cavity.

   - Operational monitoring: helped in providing ore flow continuity during the reactivation process. In order to do so, the following KPIs apply:

     - Secondary breakage frequency: drawpoints must have at least one secondary breaking activity daily only in cases when hang-ups are observed.

     - Mucking cycles: drawpoints have to achieve a minimum of 10 buckets daily. If hang-ups occurred, secondary breakage must be planned as soon as possible.

5. Drawpoint reactivation sequence: defines the direction of cave re-initiation, starting from the existing caved ore flow zone and extending towards the footprint periphery to promote a natural cave re-growth. This step considers evidence from El Teniente mine related to non-uniform and isolated draw after prolonged ore flow inactivity, which may lead to significant mobilisation of wet compacted material, high-stress redistribution and increase in frequency of mud events. Additionally, the reactivation sequence has to be dynamic and flexible in order to incorporate ground response and lessons learned through the process, which may include experiencing convergences, collapses, seismic response, as well as enhanced understanding on mud behaviour.

   When local instabilities emerge, the activities must be suspended, and a new sequence should be studied to minimise stress concentration, uncontrolled water and mud mobilisation, and personnel exposure. This adaptive sequence process ensures that drawpoint reactivation safely contributes to reserves recovery while maintaining adequate operational risk levels.

It is important to note that, even though seismic response is not an indicator of performance itself, seismicity plays a key role in providing access guidelines and procedures into the extraction level for carrying out the reactivation framework.

4 Results and discussion

This section provides the results and key lessons learned from the ore flow reactivation framework, which were obtained through site trials conducted at selected abandoned drawpoints in Dacita mine. This area was chosen as a representative case due to the presence of both a steady flow cave and a historical exposure to water–mud conditions. Figure 5 indicates the selected drawpoints to test the reactivation framework (in grey colour).

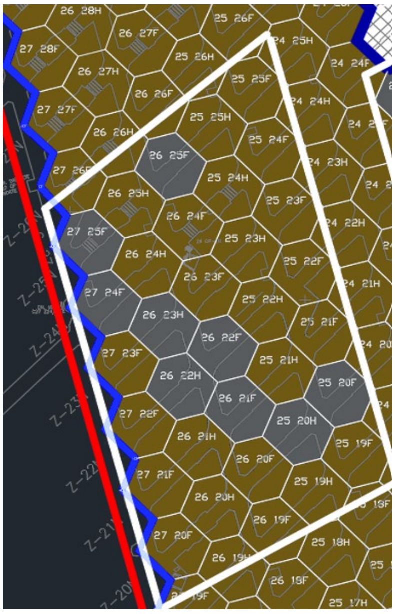


Figure 5 Plan view of the drawpoints considered for testing at Dacita mine. The colours indicate the drawpoint status, which are active ore flow (shown in light brown) and inactive ore flow (shown in grey)

4.1 On site control and monitoring

Based on the georeferenced image shown in Figure 4, an estimation of distance to surface for each drawpoint is conducted as shown in Figure 6.

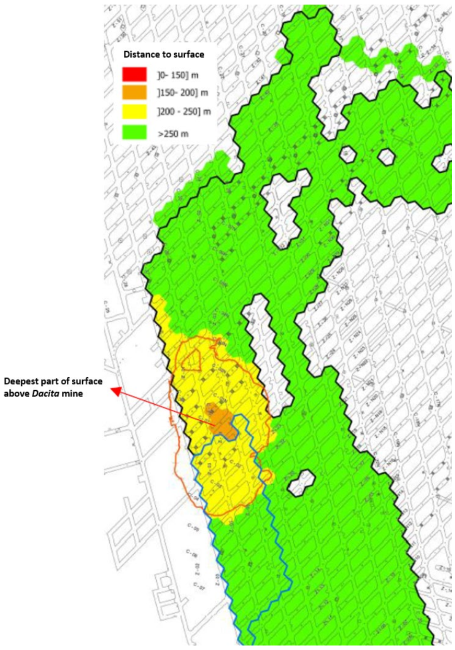


Figure 6 Plan view of the distance to surface estimation for drawpoints at Dacita mine

Once the distance to surface is obtained, and combined with ground control variables such as water content and proportion of fine material at drawpoints, draw strategies are defined for all drawpoints within the footprint. As an example, for those drawpoints with distance to surface ranging from 150 to 200 m, the drawpoint classification system considers them as 'critical drawpoints', where ore sampling has to be done once a week and the maximum draw rate is 0.2 t per day/m^2. This step is also completed using the mud rush risk map presented in Figure 2b for providing preventive measures to minimise the occurrence of sudden mud rushes during operating.

4.2 Extraction performance and secondary breakage

The implementation of controlled extraction and continuous secondary breakage strategies showed relevant outcomes in drawbell in situ conditions. Operational experience confirmed that, in all the tested drawpoints, the draw strategy effectively promoted the formation of an airgap in the brow area, without triggering uncontrolled mobilisation or inrush of water-saturated fine ore from drawpoints. Figure 7 exhibits the results of a georeferenced scanner inside one of the drawbells under study, where the theorical ellipsoid shape is observed as expected.

The achievement of this airgap signified an unprecedented milestone in the reactivation process as it enabled safe access to better understand mud material behaviour and to provide drill-and-blast designs for further activities.

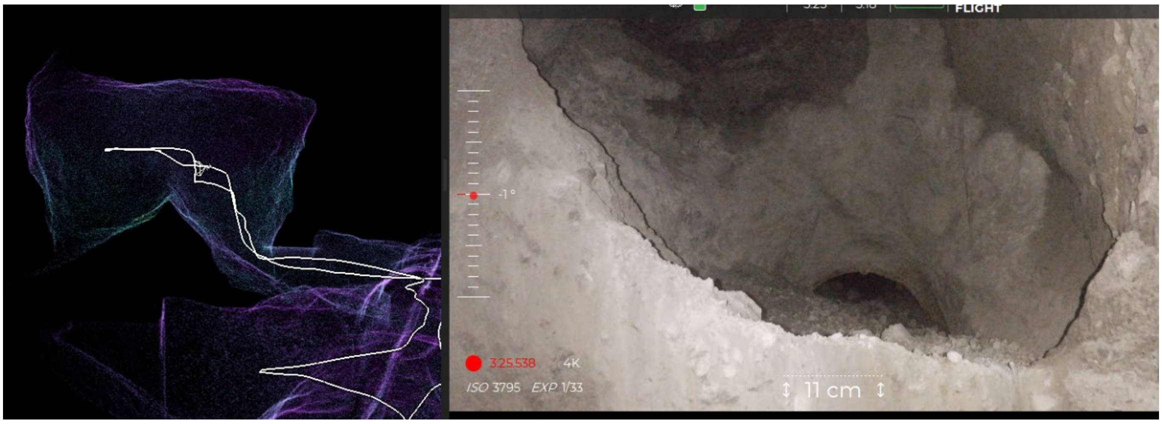
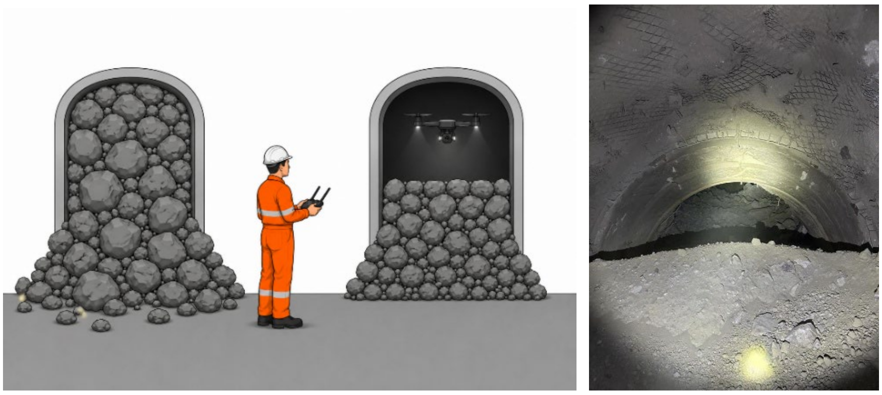


Figure 7 Georeferenced scanner inside a drawbell showing the results of continuous extraction and secondary breakage activities

Even though the airgap has the beneficial effect of creating a free face for blasting, georeferenced scanning is carried out using a drone, considering additional safety measures. First, a stabilisation period of 2 hours is applied, involving a halt in ore drawing in the drawpoint of interest and its neighbouring drawpoints in order to minimise the risk of inrush events during activities in the extraction drive. Then, the drone is operated at a safe distance, with the operator securely positioned between 2 drawpoints. A barrier is created using ore at each drawpoint, with open brows along the drive to prevent rockfalls, as illustrated in Figure 8.

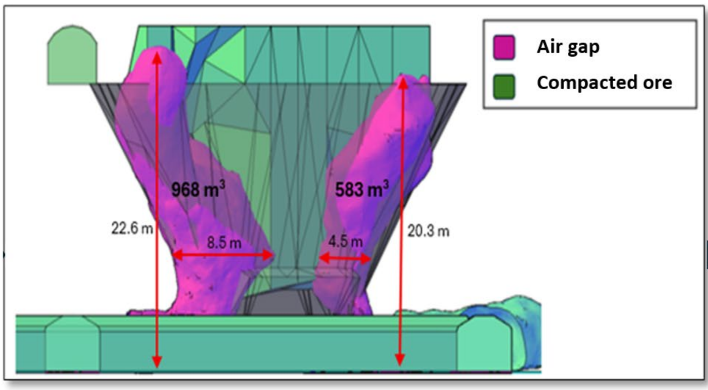


(a) (b)

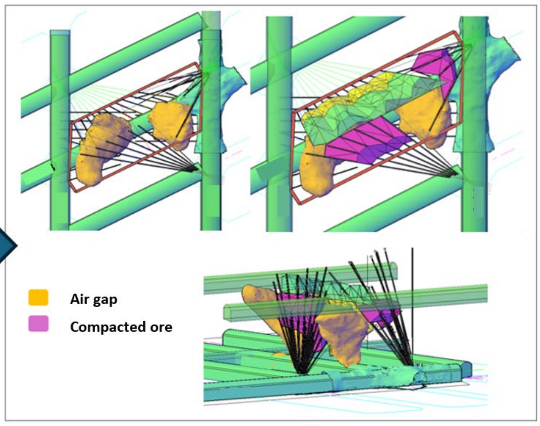
Figure 8 (a) Schematic representation of personnel operating the georeferenced drone near an open brow; (b) Ore barrier placed in front of an open brow during the study

4.3 Drill and blasting design

Once the airgap volume was reached in the previous step, georeferenced cavity scanning was successfully conducted inside the drawbell of the studied drawpoints. These scans provided high-resolution geometric data of the initial cavity, enabling the design of drill-and-blast designs based on current as-built geometries rather than assumed or theoretical cavity conditions. Drilling and blasting designs were developed as presented in Figure 9, and then sequentially implemented.



(a)



(b)

Figure 9 (a) Estimation of the airgap from georeferenced scanners; (b) Development of drill-and-blast design for this particular condition

The execution of these designs resulted in a substantial increase of the airgap volume within the drawbell, enhancing the connectivity between drawpoints and generating some controlled instabilities of compacted ore columns (Figure 10). It is important to mention that some drawpoints exhibited a better material mobilisation and progressive restoration of gravitational ore flow was observed in situ; on the other hand, an increase in the airgap did not immediately result in restoring the ore flow for the remaining drawpoints. Thus, this finding highlights the complexity of natural wet ore flow as well as the importance of cavity geometry, material saturation, fines content and stress redistribution in mature cave environments.

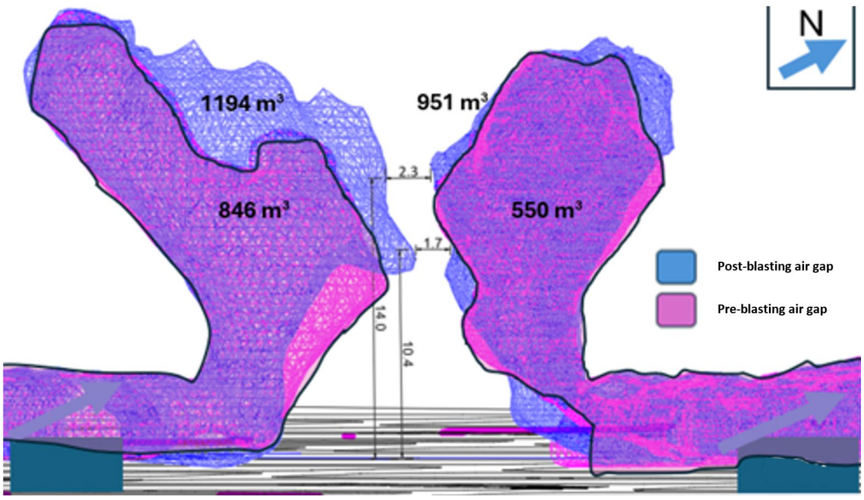
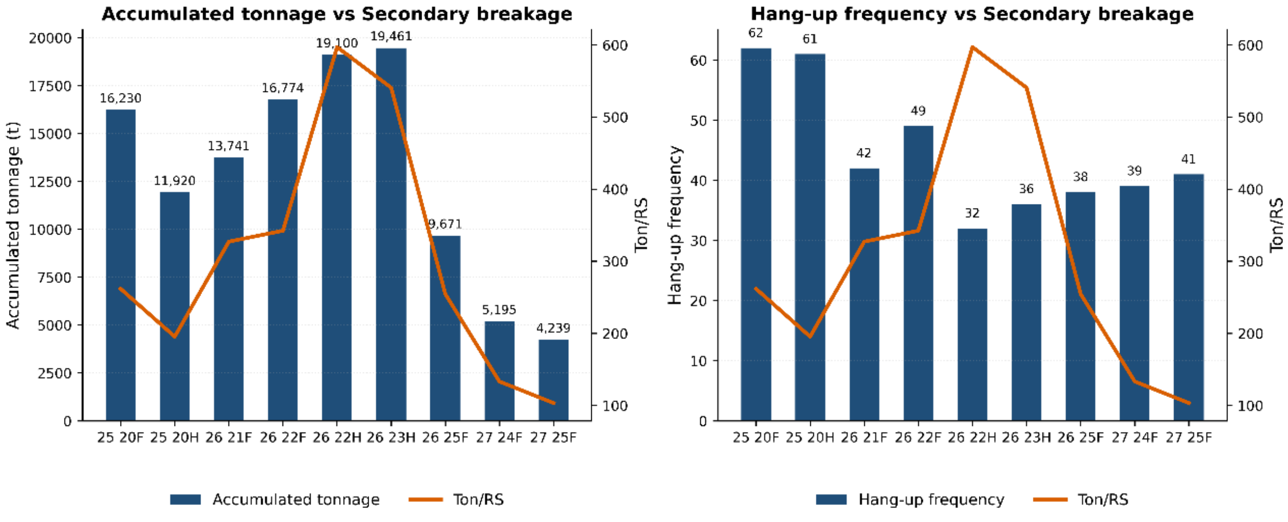


Figure 10 Georeferenced scanner showing the post-blasting results inside a drawbell

4.4 Control and monitoring

The reactivation of ore flow requires, after conducting the drill-and-blast activities, a continuous process of drawn ore along with intensive secondary breakage. Figure 11 shows the accumulated tonnage and hang-up frequency for all the test drawpoints, which are 2 of the main indicators for controlling the flow reactivation. In this step, the reactivation framework begins an iterative reactivation process, acknowledging that some drawpoints require intensive monitoring before reaching a sustained natural flow.



(a) (b)

Figure 11 Example of the main operational indicators for restoring gravity flow at abandoned drawpoints. (a) Accumulated tonnage; (b) Hang-up frequency

In these cases, continuous extraction and secondary breakage were executed under strict operational controls until the success indicators in Figure 11 were achieved. The iterative control and monitoring approach proved effective in progressively changing local conditions, such as reducing confinement and decreasing local permeability due to gradual stress transfer, until natural gravity flow accounts for reactivation state for abandoned drawpoints.

It is expected that this progressive change in local conditions allows ore to be drawn at low rates during the initial stages due to wet material compaction, until the natural flow is restored. This observation is consistent with the fact that the cycle of continuous extraction and secondary breakage provides sufficient ore tonnage to support the implementation of uniformity of draw strategies over time. Figure 12 illustrates the actual behaviour of ore drawn during the flow reactivation process at one of the drawpoints in the case study.

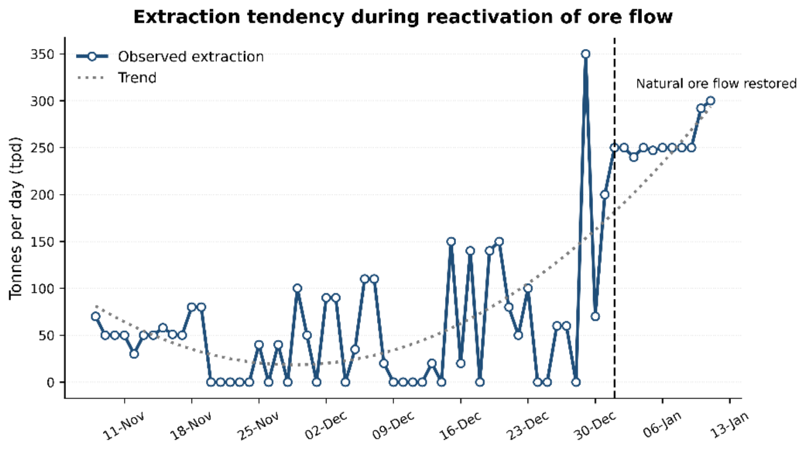


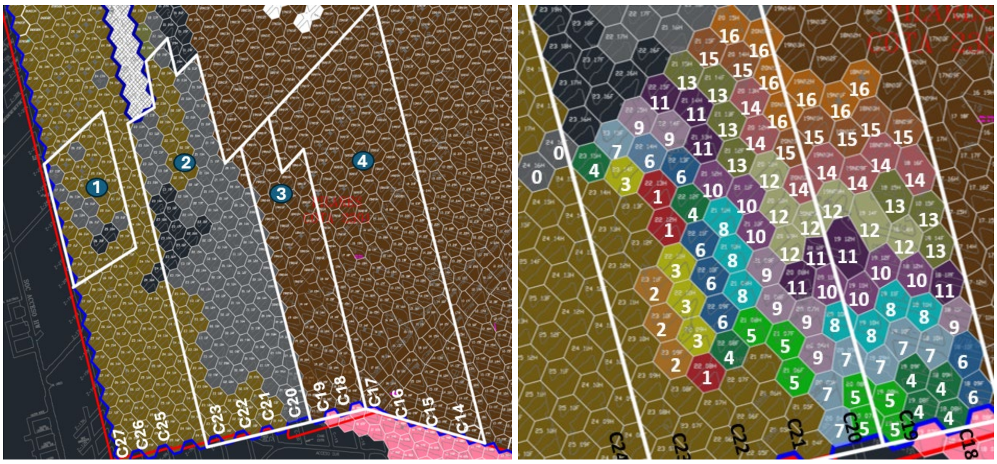
Figure 12 Resultant draw behaviour while performing the reactivation framework for a drawpoint

Based on data, the natural ore flow of a reactivated drawpoint provides a steady draw rate after experiencing tonnage fluctuations during the extraction and secondary breakage cycle, as seen in Figure 12. Once drawpoints reached this steady-state condition, the brow becomes filled with coarse caved rock mixed with fines. The coarse ore mainly consists of primary rock, generally dry and associated with dacite porphyry. In contrast, the fines contain high clays and a significant percentage of water (5–9%). Figure 13 presents 2 cases in which coarse and dry ore is naturally flowing from the drawpoint brow once the reactivation process is completed. Observations during this process suggest that the increase in moisture after reactivating a drawpoint is a consequence of removing the blockage caused by mud compaction (or 'stuck mud') within the ore column. All drawpoints tested using this framework were successfully reactivated at Dacita mine.

Figure 13 Drawpoint conditions and ore characteristics after flow reactivation at the study area

4.5 Ore flow reactivation sequence

The lessons learned from the study were used to evaluate a cave re-initiation sequence for the remaining abandoned drawpoints at Dacita and Reservas Norte mines. The mining sequence starts from the reactivated study area and then advances toward the northeast of the footprint. Figure 14a presents the sequence divided into 4 zones, comprising 10 extraction drives and 321 drawpoints planned for reactivation over the next 5 years. Based on this re-initiation sequence, it may be possible to recover an additional 38,500 tpd of abandoned ore reserves .



(a) (b)

Figure 14 (a) Reactivation sequence of abandoned drawpoints, considering 10 extraction drives and 321 drawpoints; (b) Short-term reactivation sequence for the next months. Active ore flow is shown in light brown, inactive ore flow at Dacita mine is shown in grey and inactive ore flow at Reservas Norte mine is shown in dark brown.

Zone 1 corresponds to the study area, and Zone 2 is part of Dacita mine, whereas zones 3 and 4 are located within the Reservas Norte mine. Zones 2 and 3 are of particular interest for short-term reactivation planning. Figure 14b provides the detailed monthly sequence for drilling and blasting activities. Overall, this short-term re-initiation sequence enables changes in confinement within the abandoned cave, as there is the possibility of connecting to an existing caved ore flow zone.

5 Conclusion

This study provides the operational experience on reactivating the ore flow of abandoned mud-affected drawpoints in a caving operation. The results obtained from in situ trials at Dacita mine confirmed that abandoned drawpoints, previously closed due to the presence of wet material and mud rush risk, can be progressively restored to production through controlled draw strategies, continuous secondary breakage, and disciplined monitoring. The successful reactivation of the tested drawpoints through this methodology represents a significant opportunity for recovering significant quantities of abandoned reserves in caving mines.

The key outcome of this work is the role of airgap development within the drawbell as an enabling condition for gravitational flow reactivation. Draw and secondary breakage strategies proved effective in generating stable airgaps without triggering uncontrolled inrushes of saturated fine ore. This cavity facilitated both stress redistribution and reduced confinement of compacted material. The application of georeferenced scanning inside the drawbell allows the development of as-built drill-and-blast designs that were successfully implemented in situ.

Airgap development and drill-and-blast techniques are necessary steps but not sufficient conditions to restore ore flow. Iterative cycles of extraction, secondary breakage and ground monitoring were critical activities before achieving sustained ore flow reactivation. This finding confirms the non-linear response of wet, fine caved material and emphasises the need for adaptive operational strategies.

Ultimately, future work should focus on extending the reactivation framework by incorporating other potential applications such as hydraulic fracturing instead of implementing a drill-and-blast design to drawbells, which may help in reducing the material porosity without the risk of pillar damage resulting from blasting.

Acknowledgement

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